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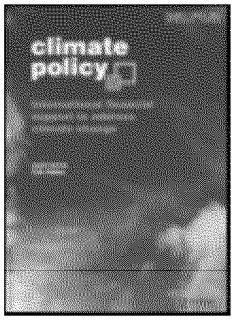

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

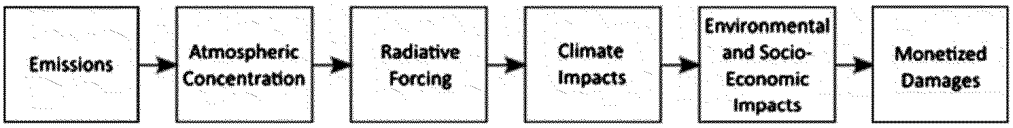

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \left(C_t^{CH_4} - C_{pre}^{CH_4}\right) - \left[f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})\right], \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln\left[1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})\right]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}. \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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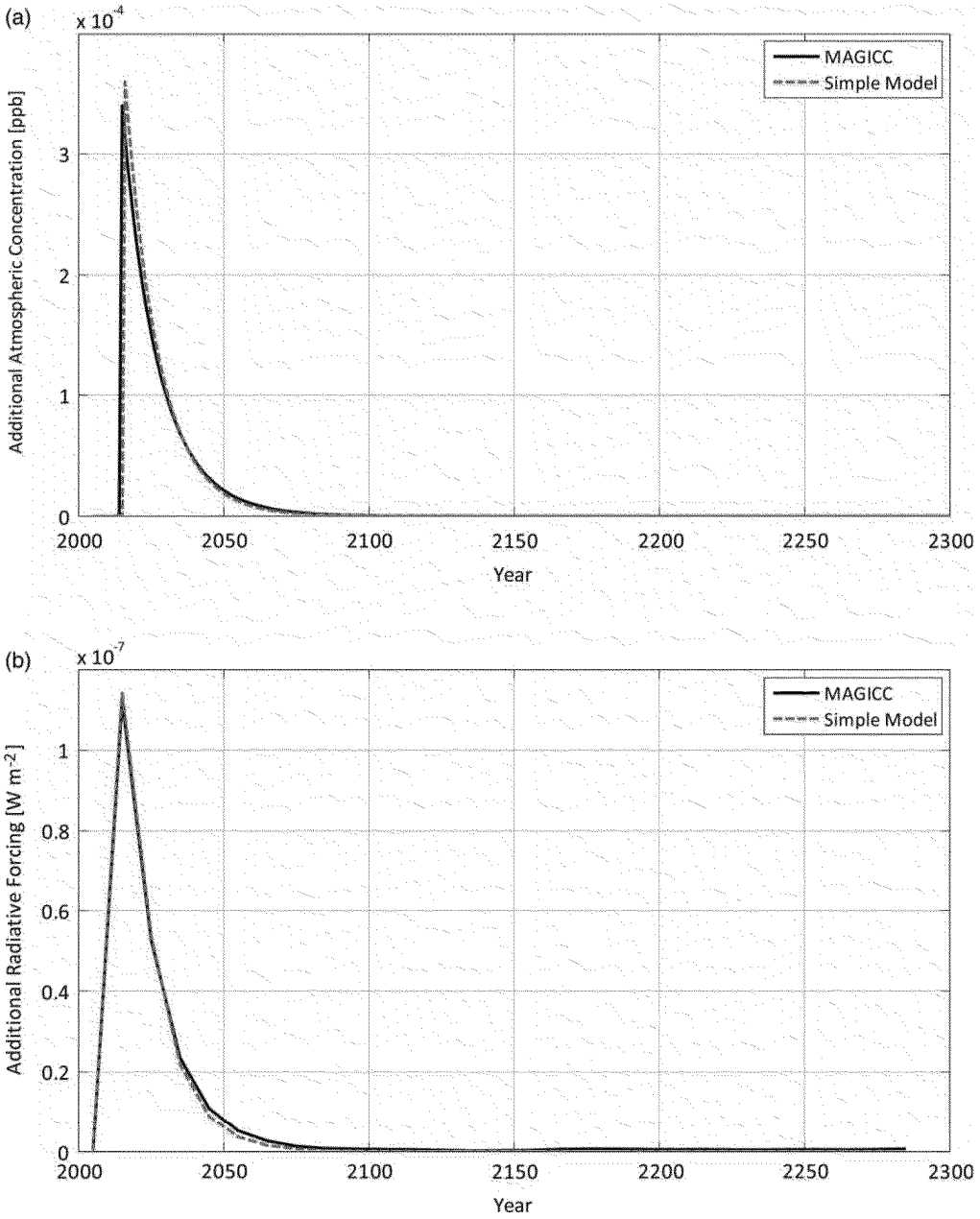

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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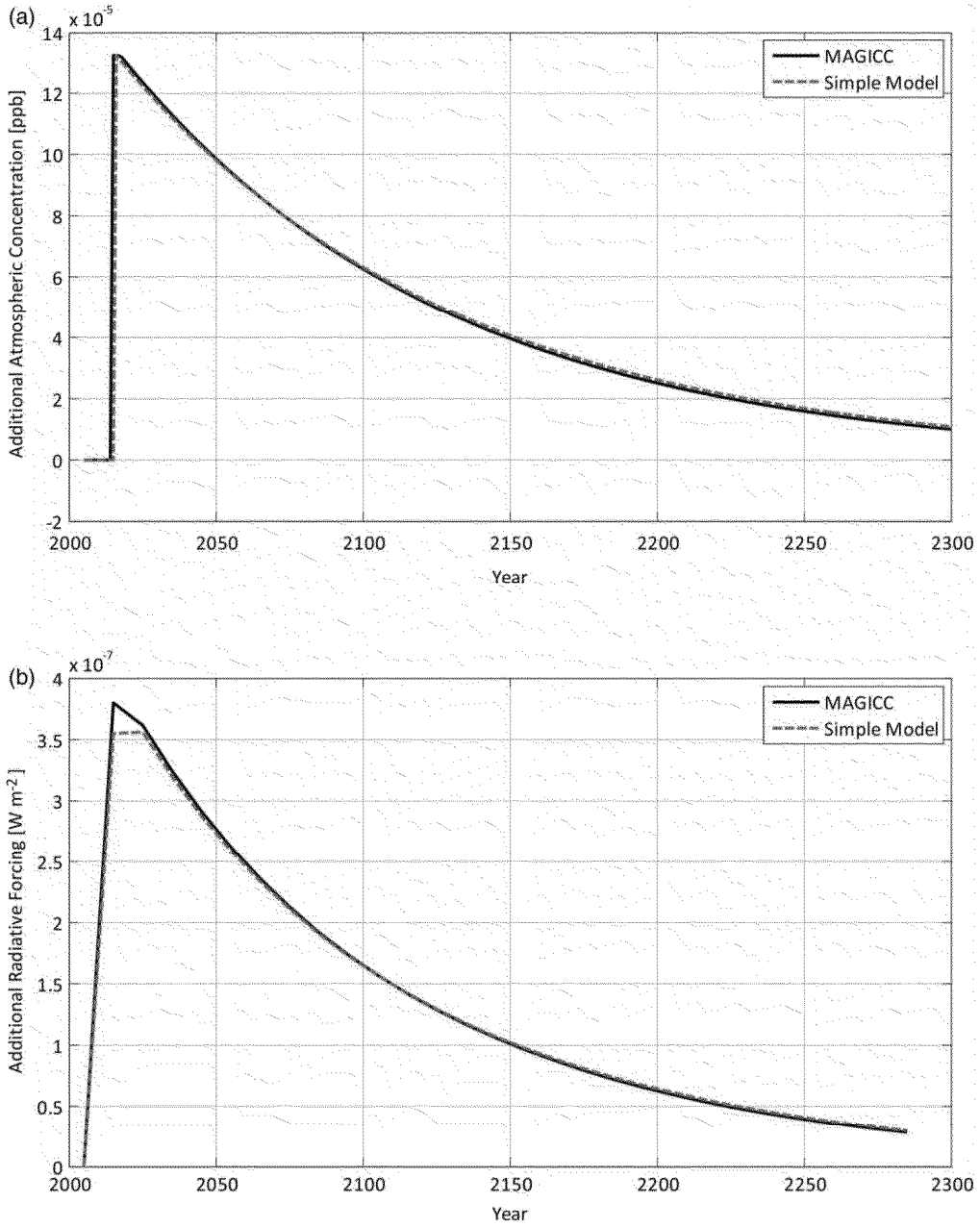

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

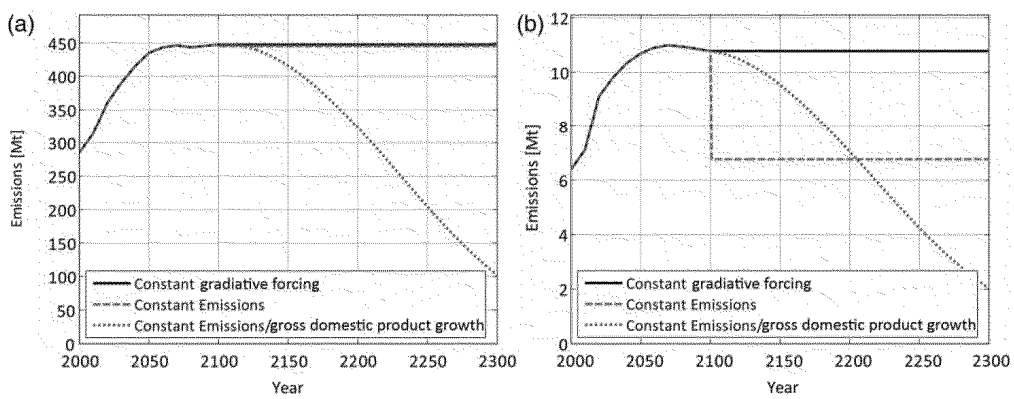

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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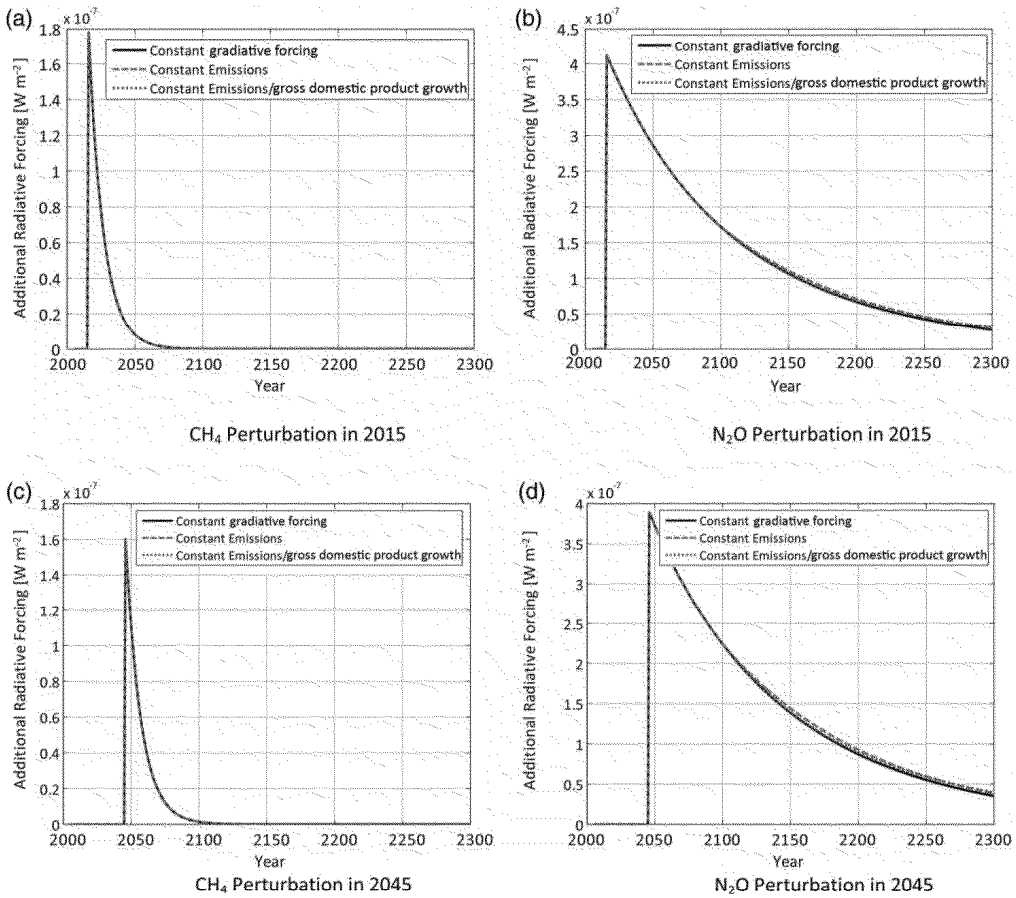

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the

deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

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Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009617

(5)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

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EPA Tracking Number EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $250, I ask that you contact me prior to proceeding.

Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

EPA TRACKING NUMBER EPA-HQ-2013-009523 (1)

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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

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I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

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I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

SIDLEY AUSTIN LLP
SIDLEY

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009617

(5)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

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EPA TRACKING NUMBER EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $250, I ask that you contact me prior to proceeding.

Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

EPA TRACKING NUMBER EPA-HQ-2013-009523 (1)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

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This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

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For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the

deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

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For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

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SIDLEY AUSTIN LLP
SIDLEY

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009517

(5)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

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EPA Tracking Number EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

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Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

EPA TRACKING NUMBER EPA-HQ-2013-009523 (1)

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1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

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1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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August 23, 2013

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3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
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SIDLEY AUSTIN LLP
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Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009517

(5)

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4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

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EPA Tracking Number EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

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Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

DONN J. VIVIANI, PhD

PETITIONERS

June 30, 2015

NOTICE OF PETITION

Gina McCarthy
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, D.C. 20460
Email: McCarthy.Gina@cpa.gov

PETITIONERS

Center for Biological Diversity
1212 Broadway #800
Oakland, CA 94612
(510) 844-7100

Donn J. Viviani, PhD
4907 Yorktown Blvd
Arlington, VA 22207
oceanpetition@gmail.com

The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

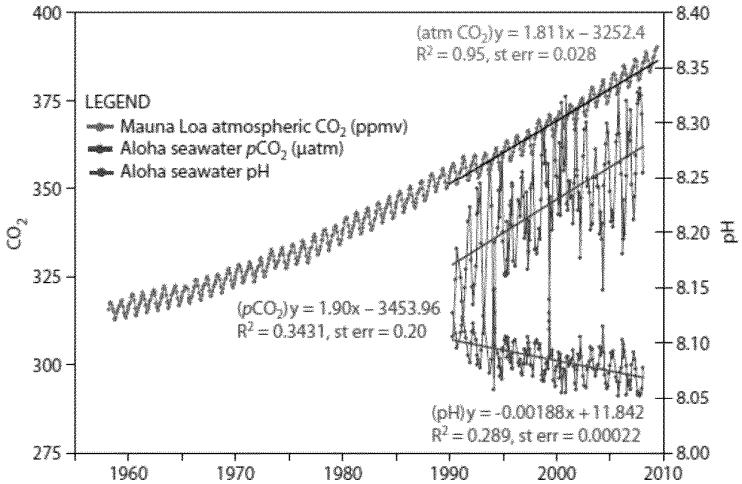

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

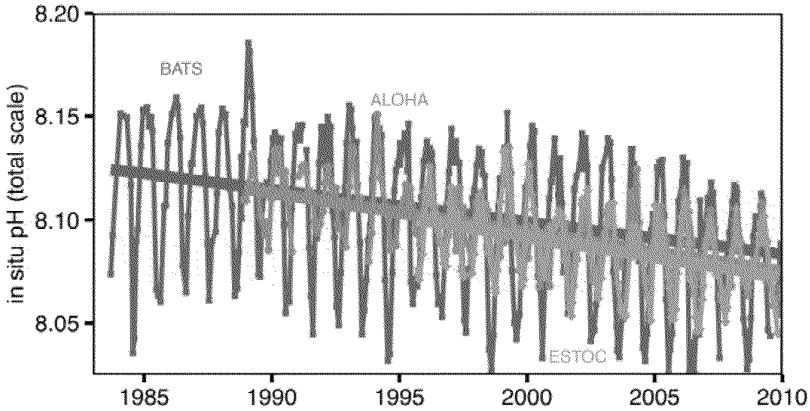

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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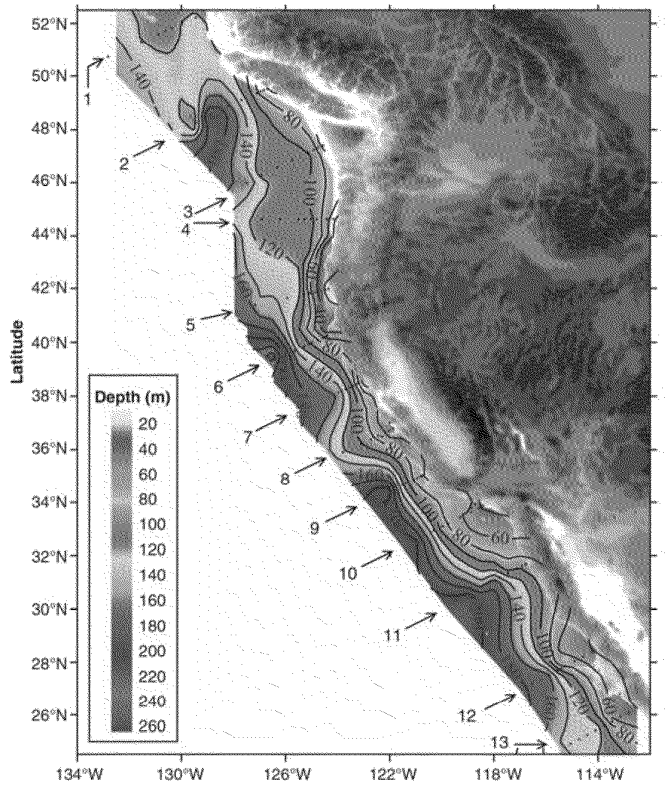

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. Alaskan Waters

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

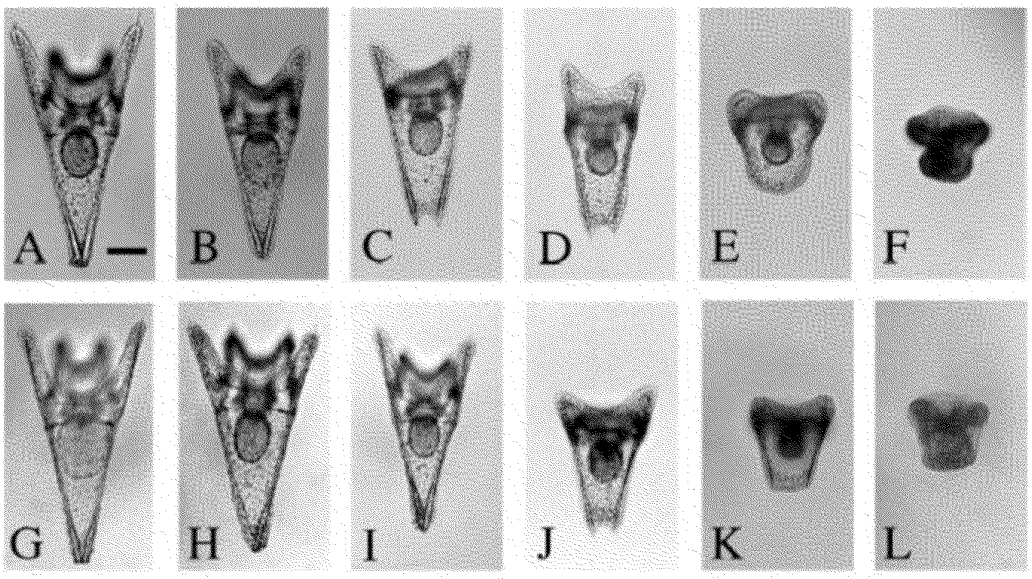

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3{:}5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2□C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5□C to 5□C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2□C and likely leading to a temperature rise of at least 3.5□C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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EPA TRACKING NUMBER EPA-HQ-2013-009523 (1)

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

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c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the

deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009618 (2)

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National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

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Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

EPA Tracking Number EPA-HQ-2013-009517

(5)

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Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

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EPA Tracking Number EPA-HQ-2013-005473

Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $250, I ask that you contact me prior to proceeding.

Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

Description Available to the Public : Yes

Has Request Been Modified? ☐

Attached Supporting Files

No supporting files have been added.

BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

DONN J. VIVIANI, PhD

PETITIONERS

June 30, 2015

NOTICE OF PETITION

Gina McCarthy
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, D.C. 20460
Email: McCarthy.Gina@cpa.gov

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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

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[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

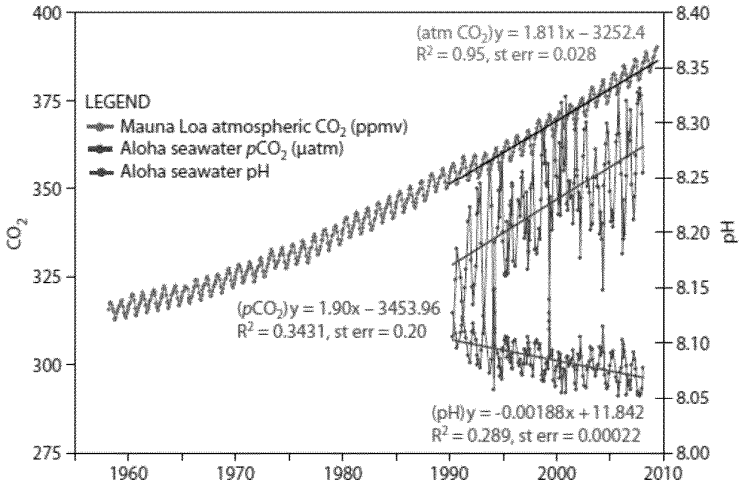

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

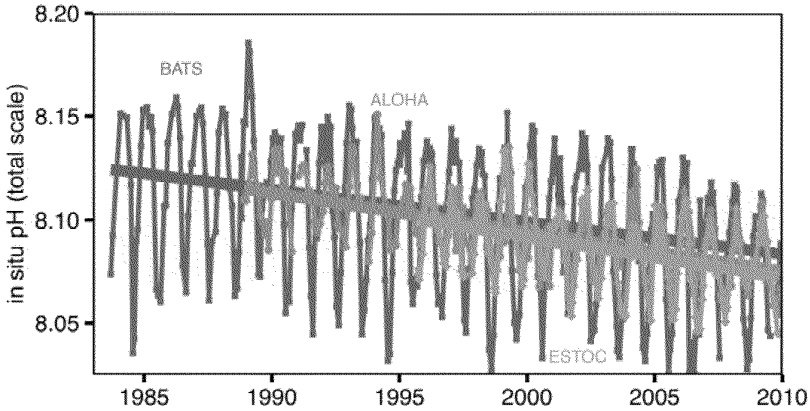

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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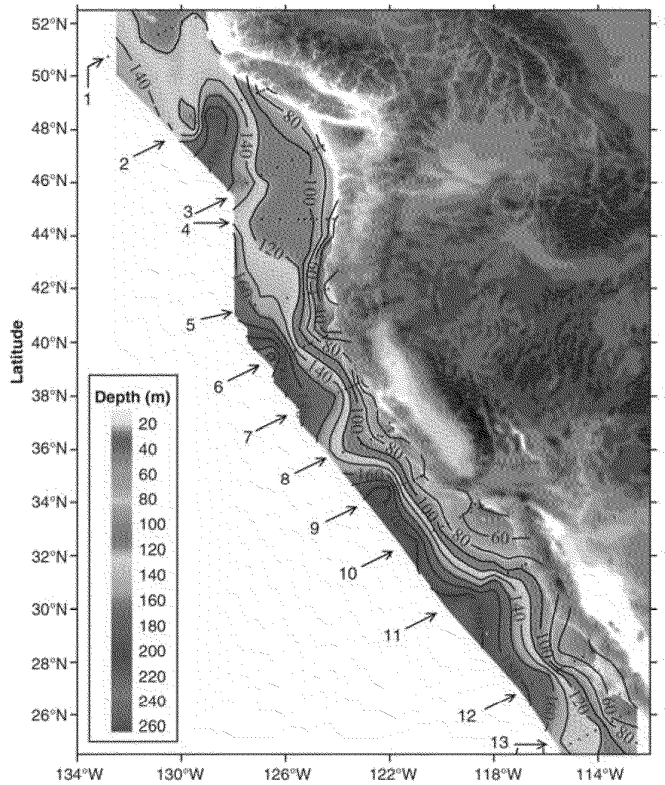

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. *Alaskan Waters*

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

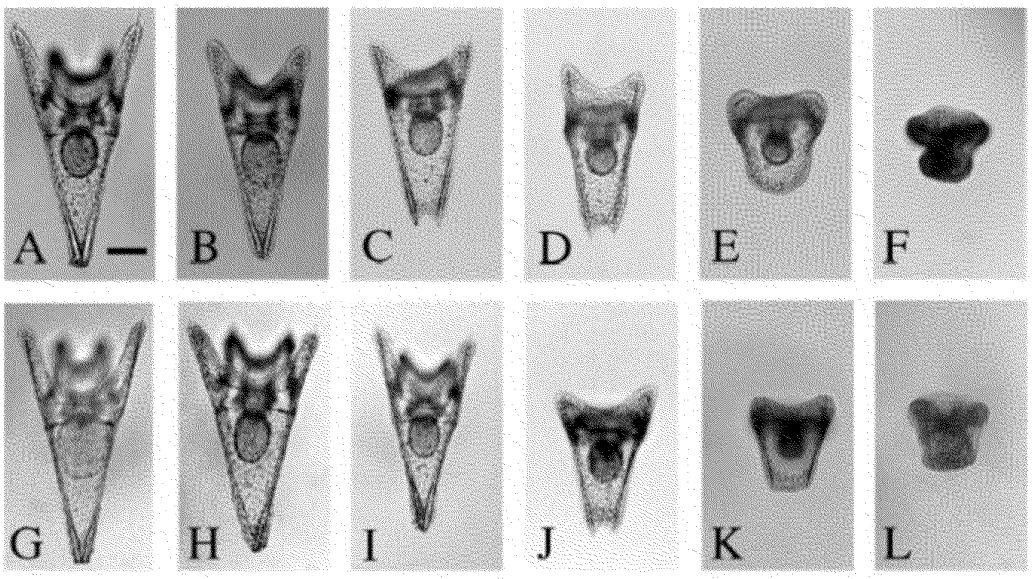

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3{:}5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2°C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5°C to 5°C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2°C and likely leading to a temperature rise of at least 3.5°C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

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PETITIONERS

June 30, 2015

NOTICE OF PETITION

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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

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[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

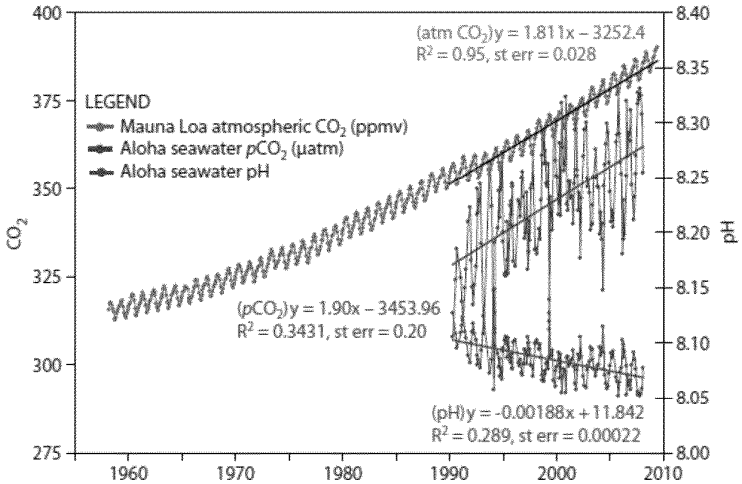

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

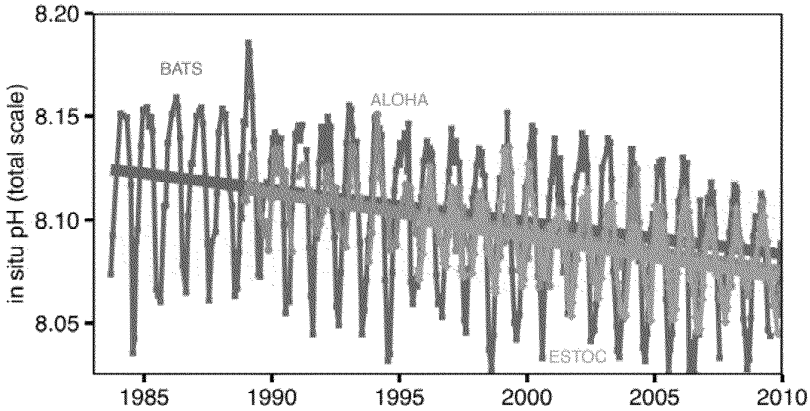

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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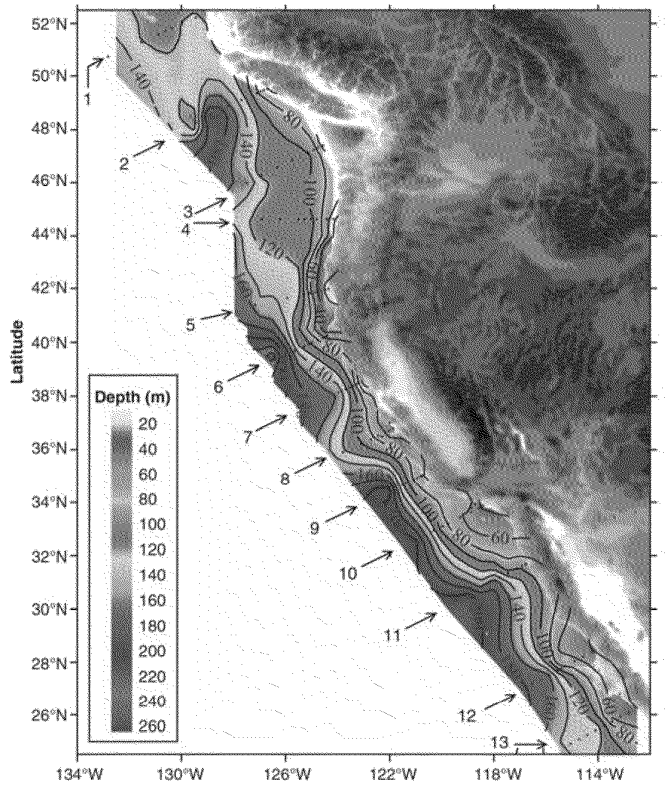

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. *Alaskan Waters*

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

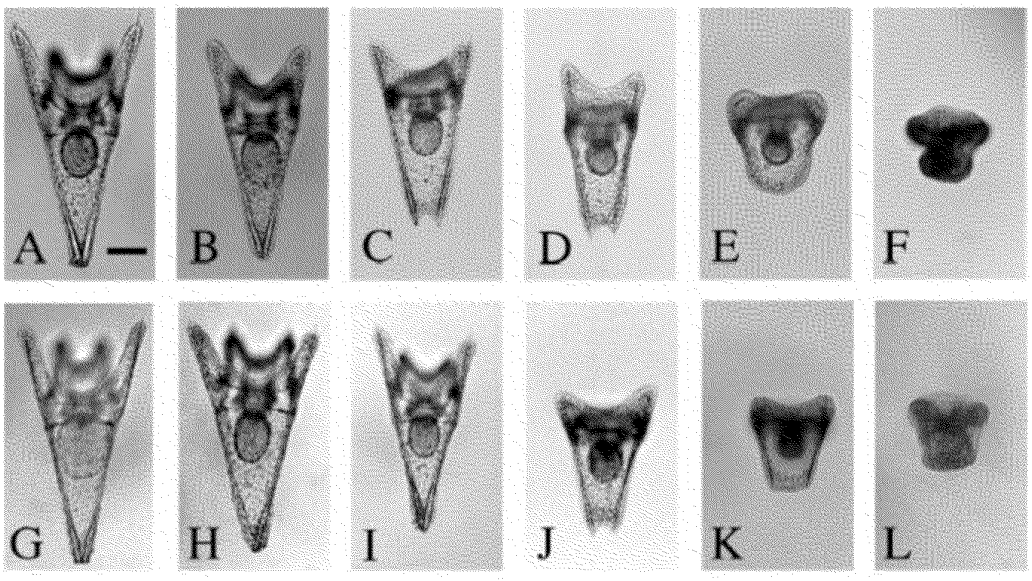

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3{:}5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2°C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5°C to 5°C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2°C and likely leading to a temperature rise of at least 3.5°C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

DONN J. VIVIANI, PhD

PETITIONERS

June 30, 2015

NOTICE OF PETITION

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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

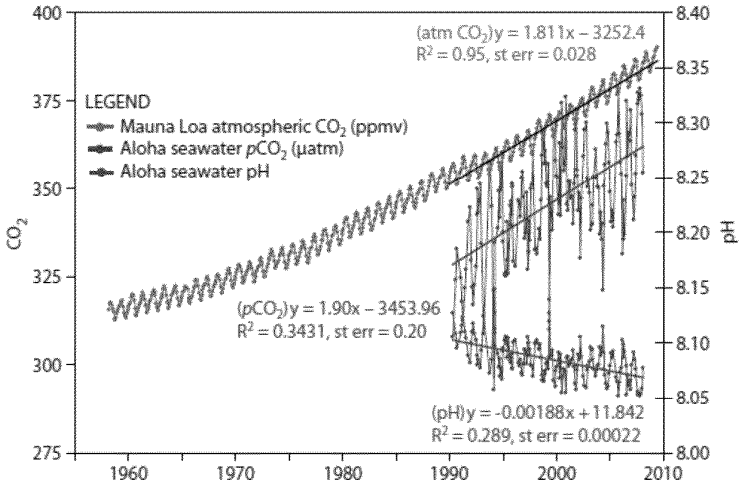

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

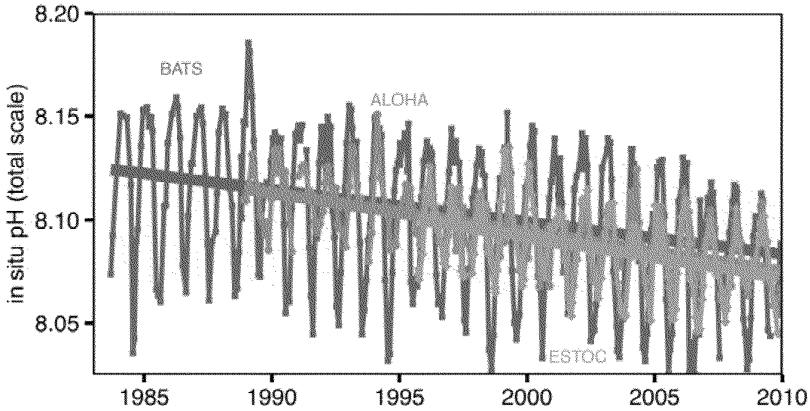

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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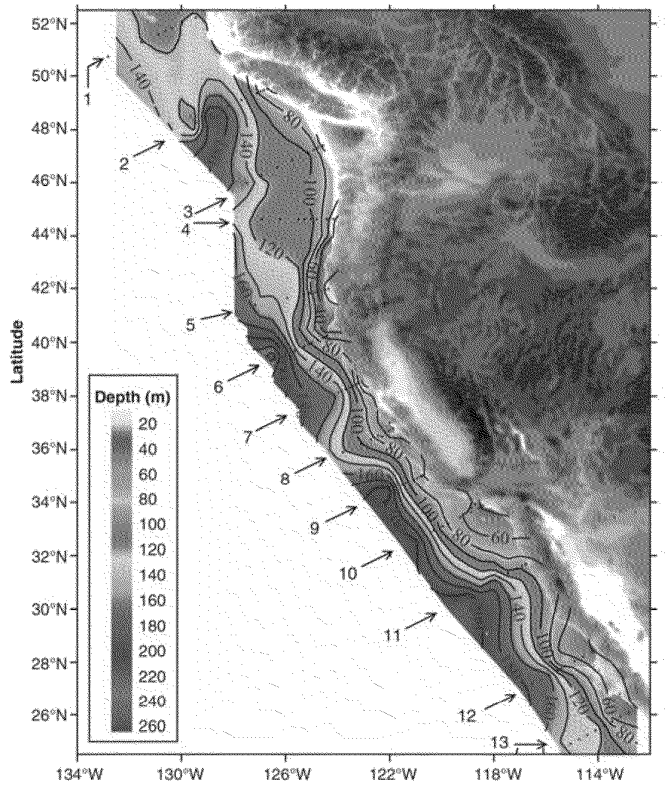

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. *Alaskan Waters*

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

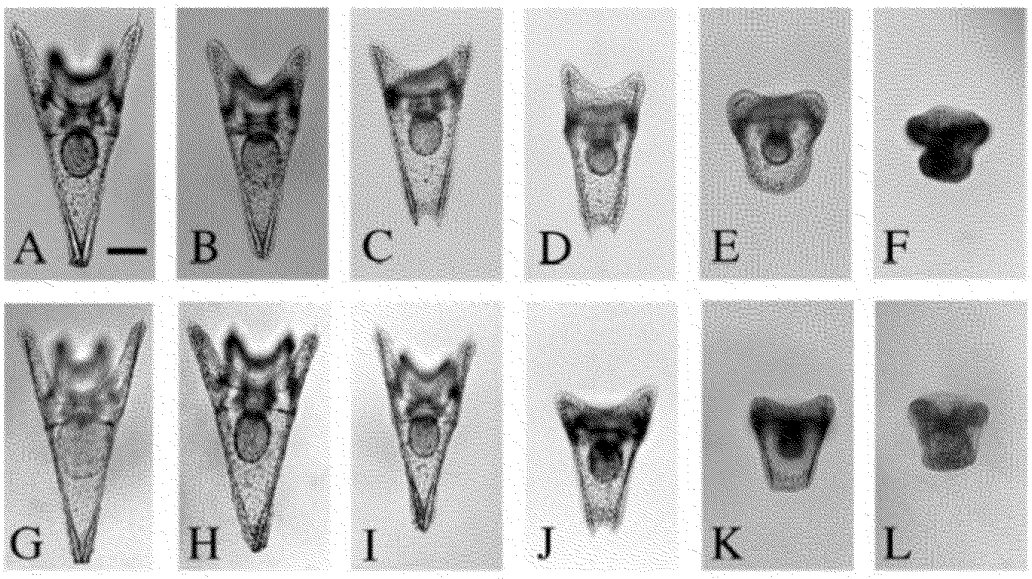

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3:5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2°C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5°C to 5°C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2°C and likely leading to a temperature rise of at least 3.5°C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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BEFORE THE ENVIRONMENTAL PROTECTION AGENCY

PETITION FOR RULEMAKING PURSUANT TO SECTION 21 OF THE TOXIC SUBSTANCES CONTROL ACT, 15 U.S.C. § 2620, CONCERNING THE REGULATION OF CARBON DIOXIDE

Credit: NOAA

CENTER FOR BIOLOGICAL DIVERSITY

DONN J. VIVIANI, PhD

PETITIONERS

June 30, 2015

NOTICE OF PETITION

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The Center for Biological Diversity ("Center") is a non-profit, public interest environmental organization dedicated to the protection of native species and their habitats through science, policy and environmental law. The Center has over 800,000 members and online activists throughout the United States and around the world. The Center's Oceans Program and its supporters are specifically concerned with the conservation of marine species, the preservation of ocean ecosystems and the effective implementation of U.S. environmental laws, including the Toxic Substances Control Act. The Center submits this petition on its own behalf and on behalf of its members and staff with an interest in protecting the marine environment.

Donn J. Viviani, PhD, is a retired U.S. Environmental Protection Agency scientist. He was the Director of the Climate Policy Assessment Division in the Office of Policy, Economics and Innovation. He also served as Chairman of the Great Lakes Water Board's Toxic Substances Committee and as a member of the Science Coordinating Committee for the International Joint Commission for the Great Lakes. Dr. Viviani enjoys the ocean and submits this petition, in part, so his grandchildren will be able to enjoy it as well. Dr. Viviani also submits a supplement to the petition, under his signature only, and respectively requests that it be considered.

ACTION REQUESTED

Pursuant to section 21 of the Toxic Substances Control Act ("TSCA" or the "Act"), 15 U.S.C. § 2620, and section 553(e) of the Administrative Procedure Act ("APA"), 5 U.S.C. § 553(e), the Center for Biological Diversity and Donn J. Viviani (collectively, "Petitioners") hereby petition the Administrator of the U.S. Environmental Protection Agency ("EPA") to promulgate regulations protecting public health and the environment from the serious harms associated with anthropogenic emissions of carbon dioxide, including ocean acidification. Specifically, Petitioners request that EPA adopt a rule under section 6 of the Act, 15 U.S.C. § 2605, requiring manufacturers and processors to mitigate these emissions.

This petition sets in motion a specific process, placing definite response requirements on EPA. Specifically, TSCA stipulates that the agency "*shall* either grant or deny the petition" within 90 days following its receipt, "promptly commenc[ing] an appropriate [rulemaking]

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proceeding" if such action is warranted. 15 U.S.C. § 2620(b)(3) (emphasis added). Conversely, should EPA deny this petition, the agency must publish the reasons for denial in the Federal Register. 15 U.S.C. § 2620(b)(3); *see also* 5 U.S.C. § 555(e) ("Prompt notice shall be given of the denial in whole or in part of a written application, petition, or other request of an interested person made in connection with any agency proceeding."). Pursuant to 15 U.S.C. § 2620(b)(4), petitioners may file suit in federal district court to challenge an adverse or untimely determination. *See also* 5 U.S.C. §§ 702, 706.

As described in this petition, anthropogenic emissions of carbon dioxide satisfy the standard for regulation set forth at 15 U.S.C. § 2605. For example, EPA has acknowledged that these emissions have the potential to alter ocean chemistry, thus imperiling important marine ecosystems and presenting an unreasonable risk of injury to the environment. Accordingly, the agency must promptly commence the proposed rulemaking to reduce and mitigate these harms. In the event that EPA concludes that there are insufficient data and experience upon which to determine or predict the effects of carbon dioxide emissions, we alternatively request that the agency adopt a rule under section 4 of the Act, 15 U.S.C. § 2603, requiring manufacturers and processors responsible for the generation of carbon dioxide to undertake testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Dated this 30th day of June 2015.

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INTRODUCTION

Ocean acidification — caused by carbon dioxide ("CO_2") emissions — is a severe threat to the marine environment and the health of people who depend on oceans and coasts. Because of the unreasonable risk that CO_2 poses to the environment and human health, this petition seeks rulemaking under the Toxic Substances Control Act ("TSCA") to regulate CO_2 from cradle to grave.

About 28% of CO_2 emissions from power generation, cement production, industry, and other sources are absorbed by the ocean. These CO_2 emissions cause seawater to become more acidic and corrosive to sea life. Anthropogenic CO_2 emissions have increased the acidity of the oceans on average by 30%, and by the end of the century scientists predict that the oceans will become 150-170% more acidic.

While the most dangerous consequences of CO_2 on our oceans are still to come, harmful impacts on the environment are already well-documented.

- Billions of oyster larvae have perished in the Pacific Northwest due to ocean acidification;
- 53% of pteropods, plankton that form the base of the marine food web, along the West Coast have severely dissolved shells because of the corrosive nearshore conditions; and
- Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%.

These are just some of the harmful environmental impacts of ocean acidification caused by CO_2 emissions. Anthropogenic CO_2 emissions are contributing to increasingly corrosive conditions for marine animals, and will continue to grow more severe absent actions to promptly reduce CO_2 pollution in the atmosphere.

TSCA was enacted in part to address the threat of ozone depletion caused by chlorofuorocarbon (CFC) emissions. And here again TSCA regulation is needed where airborne emissions are causing damage to our environment — this time threatening ocean ecosystems, fish and shellfish industries, and communities that depend on oceans and coral reefs.

Petitioners specifically request that EPA take the following actions:

1. **Make a determination under TSCA § 6 that CO_2 presents an unreasonable risk of injury to health or the environment; and**
2. **Initiate rulemaking to control CO_2; or**
3. **If EPA finds data inadequate to make a §6 determination then EPA must initiate rulemaking for testing under TSCA § 4.**

This petition presents scientific evidence that establishes that CO_2 presents an unreasonable risk of injury to the environment, and therefore EPA must take action under TSCA section 6.

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I. The Toxic Substances Control Act

Congress enacted TSCA, 15 U.S.C. §§ 2601 *et seq.*, "to assure that … innovation and commerce in … chemical substances and mixtures do not present an unreasonable risk of injury to health or the environment."[1] Accordingly, lawmakers required those responsible for the manufacture and processing of these compounds to develop "adequate data" describing their effects, and authorized EPA to devise and implement reasonable controls to prevent the risk of injury to health or the environment.[2]

Section 6 of TSCA mandates that EPA "shall" regulate a chemical substance for which

> there is a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance or mixture, or that any combination of such activities, presents or will present an unreasonable risk of injury to health or the environment.[3]

Permissible regulations include requirements prohibiting or "limiting the amount of such substance … which may be manufactured, processed, or distributed in commerce."[4] EPA can also require processors "to give public notice of such risk [of injury], and . . . to replace or repurchase such substance . . . to adequately protect health or the environment."[5] In assessing risk, EPA must consider:

> (A) the effects of such substance or mixture on health and the magnitude of the exposure of human beings to such substance or mixture,
> (B) the effects of such substance or mixture on the environment and the magnitude of the exposure of the environment to such substance or mixture,
> (C) the benefits of such substance or mixture for various uses and the availability of substitutes for such uses, and
> (D) the reasonably ascertainable economic consequences of the rule, after consideration of the effect on the national economy, small business, technological innovation, the environment, and public health.[6]

Thus, if there is a reasonable basis to conclude that a proposed rule is necessary to protect the environment, then EPA must grant a petition for rulemaking and initiate rulemaking procedures. Factual certainty is not required; instead, the agency may "base its action on scientific theories, consideration of projections from available data, modeling using reasonable assumptions, and extrapolations from limited data."[7] Even if EPA determines that another federal law "could

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[1] 15 U.S.C. § 2601(b)(3) (2012). Within the meaning of TSCA, the term "chemical substance" includes "any organic or inorganic substance of a particular molecular identity." *Id.* § 2602(2).
[2] *Id.* § 2601(b)(1) & (2).
[3] *Id.* § 2605(a) (emphasis added).
[4] *Id.* § 2605(a)(1)(B).
[5] *Id.* § 2605(b)(2)(B).
[6] *Id.* § 2605(c)(1). E.
[7] Lead Fishing Sinkers; Response to Citizens' Petition and Proposed Ban, 59 Fed. Reg. 11,122, 11,138 (Mar. 9, 1994) (*citing* H.R. Rep. No. 1341, 9th Cong., 2d Sess. 32 (1976)).

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[sufficiently] eliminate[] or reduce[]" the risk associated with a particular chemical substance, the agency may elect to regulate the substance under TSCA, provided that a "comparison of the estimated costs" and "relative efficiency" reveals that such action promotes the public interest.[8]

In the event that EPA lacks adequate data and experience upon which to determine the health and environmental risks associated with a particular chemical substance, the agency "*shall* by rule require that testing be conducted on such substance."[9] Specifically, Section 4 of the Act authorizes EPA to compel manufacturers and processors to evaluate the safety of substances that "may present an unreasonable risk of injury to health or the environment" or that "[are] or will be produced in substantial quantities" and, thus, "may reasonably be anticipated to enter the environment in substantial quantities" or result in "significant or substantial human exposure."[10] TSCA provides for testing to determine toxicity, persistence, and other characteristics which affect health and the environment and are necessary to determine if there is an unreasonable risk of injury to health or the environment.

Over forty years ago, the Council on Environmental Quality warned of the "high priority need" for a new legal authority capable of ensuring the safe use of toxic chemicals.[11] Despite TSCA's powerful potential, however, EPA has accomplished very little under the Act. This petition presents substantial scientific evidence demonstrating that anthropogenic emissions of CO_2 pose an unreasonable risk to human and environmental health. Indeed, studies show that significant and potentially irreversible harm has already occurred. As the Council recognized decades ago, "[w]e should no longer be limited to repairing [this] damage after it has been done; nor should we continue to allow the entire population or the entire environment to be used as a laboratory." Instead, EPA must take prompt action to reduce and mitigate the anthropogenic production of CO_2.

II. EPA Must Issue a Rule to Regulate or Require Tests for CO_2 Causing Ocean Acidification

CO_2 presents an unreasonable risk of injury to the environment because its exposure to the ocean changes seawater chemistry with harmful impacts on marine life and ecosystems. Substantial evidence supports this conclusion and is discussed in this petition. Accordingly, this petition seeks a rulemaking to regulate CO_2 under TSCA.

This petition requires EPA to make a determination under TSCA section 6 if the injury to the environment and health from CO_2 is unreasonable. Alternately, if the Agency demonstrates that the existing science is insufficient to make a determination under TSCA section 6, EPA must initiate test rules under TSCA section 4 to develop the missing information needed to determine if the TSCA section 6 trigger is met and how best to mitigate the harm.

A. TSCA Authorizes EPA to Act on CO_2

To enable the achievement of TSCA's ambitious objectives, Congress broadly defined EPA's jurisdiction under the Act. As described above, TSCA explicitly directs EPA to initiate

[8] *Id.*
[9] *Id.* § 2603 (emphasis added).
[10] *Id.*
[11] Council on Envtl. Quality, Toxic Substances at v (April 1971).

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rulemaking upon finding that "the manufacture, processing, distribution in commerce, use, or disposal of a chemical substance" threatens public health or the environment.[12] TSCA then authorizes the regulation of "chemical substances" that are "in commerce," a test met by CO_2. Indeed, CO_2 is already on the TSCA inventory as a "chemical in commerce."[13] CO_2 necessarily qualifies as a "chemical substance," a category that includes "any organic or inorganic substance of a particular molecular identity."[14] Moreover, the anthropogenic emissions at issue are in commerce; federal courts have previously concluded that air emissions[15] and "incidental byproducts of industrial chemical processes" are within the scope of EPA's authority under the Act.[16] Existing scientific evidence demonstrates that the anthropogenic production of CO_2 has already damaged marine ecosystems and endangered vulnerable portions of the human population. For the reasons described below, EPA must promptly reduce and mitigate these harms.

1. CO_2 Is a Chemical Substance

First, carbon dioxide is a "chemical substance" falling within the scope of the Act. The Act defines "chemical substance" as "any organic or inorganic substance of a particular molecular identity, including any combination of such substances occurring in whole or in part as a result of a chemical reaction or occurring in nature and (ii) any element or uncombined radical."[17]. CO_2 meets this definition. CO_2 is a chemical substance that occurs both in nature and as a result of a chemical reaction. It consists of a carbon atom bonded to two oxygen atoms:

$$O=C=O$$

It is identified by molecular formula CO_2 and by CAS number 124-38-9.

2. CO_2 Is in Commerce

Second, CO_2 is in commerce, and it is already on the TSCA inventory (CAS 124-38-9) with "chemical in commerce" as the stated reason for regulation.[18] Under TSCA's statutory text, "commerce" is defined as "trade, traffic, transportation, or other commerce . . . between a place in a State and any place outside of such state, or . . . which affects trade, traffic, transportation, or commerce."[19] CO_2 is primarily produced as a byproduct from the combustion of fossil fuels; according to the EPA, CO_2 emissions account for 77% of greenhouse gas emissions worldwide.[20]

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[12] *Id.* §§ 2605(a), 2603(a)(1)(A)(i), 2506(a). Although TSCA does not define "disposal," other federal environmental laws explain that this term encompasses "the discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air or discharged into any waters, including ground waters." 42 U.S.C. §§ 6903(3), 9601(29).
[13] EPA, Substance Registry at http://1.usa.gov/1IBS1w6 (last accessed June 28, 2015).
[14] 15 U.S.C. § 2602(2). This definition excludes specific compounds already subject to federal control, such as pesticides, tobacco products, nuclear materials and food, drugs and cosmetics. *Id.* § 2602(2)(B).
[15] *Citizens for a Better Env't v. Thomas*, 704 F. Supp. 149, 152 (E.D. Ill. 1989).
[16] *Envtl. Def. Fund v. Envtl. Prot. Agency*, 636 F.2d 1267, 1271 (D.C. Cir. 1980).
[17] 15 U.S.C. § 2602(2)(A).
[18] EPA, Substance Registry at http://1.usa.gov/1IBS1w6.
[19] 15 U.S.C. § 2602(3).
[20] EPA, Global Greenhouse Gas Emissions Data, http://www.epa.gov/climatechange/ghgemissions/global.html (last updated June 21, 2013; last accessed June 28, 2015).

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The most voluminous sources of greenhouse gas emissions are energy suppliers,[21] industry,[22] land use and forestry,[23] agriculture,[24] transportation,[25] commercial and residential buildings,[26] and waste and wastewater.[27] All of these emitters produce CO_2 as a byproduct of their ordinary processes.

TSCA's statutory and regulatory text support the proposition that CO_2 emitted as a byproduct of industrial processes can be regulated under TSCA because CO_2 in this context is manufactured, meaning "produce[d] . . . with the purpose of obtaining an immediate or eventual commercial advantage."[28] All of the industries listed above which emit CO_2 are performed to obtain an immediate or eventual commercial advantage, as all of these industries are commercial and part of a competitive market. Therefore, incidental production of CO_2 is manufactured or produced "for a commercial purpose," and is found "in commerce" pursuant to TSCA regulations.

Accordingly, CO_2 emissions fit the regulatory definition of a chemical substance produced for a commercial purpose. This is bolstered by the broad definition of "commerce" in the TSCA statute; at the very least, CO_2 emissions "affect" trade, traffic, transportation, and commerce.

TSCA's purpose and regulatory text support the regulation of chemical substances that are an incidental byproduct, and indeed EPA has regulated chemical byproducts under TSCA before. For example, PCBs are regulated under TSCA even when they are only incidentally produced as a byproduct of industrial processes.[29] EPA regulates PCB "byproducts" for which there are no separate commercial intents, and TSCA regulates inadvertently vented PCB emissions.[30] Moreover, EPA's authority under TSCA broadly defines what it regulates under "disposal" of PCBs to include intentional and accidental disposal.[31] EPA has also previously prohibited wastes from chemical manufacturing under TSCA.[32]

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[21] Which emit greenhouse gases through "[t]he burning of coal, natural gas, and oil for electricity and heat." *Id.*

[22] Which emit greenhouse gases through "fossil fuels burned on-site at facilities for energy" and "chemical, metallurgical, and mineral transformation processes not associated with energy consumption." *Id.*

[23] Which emit "carbon dioxide . . . from deforestation, land clearing for agriculture, and fires or decay of peat soils." *Id.*

[24] "Greenhouse emissions from agriculture mostly come from the management of agricultural soils, livestock, rice production, and biomass burning." *Id.*

[25] Which emit greenhouse gases through "fossil fuels burned for road, rail, air, and marine transportation." *Id.*

[26] Which emit greenhouse gases from "on-site energy generation and burning fuels or heat in buildings or cooking in homes." *Id.*

[27] Which emit carbon dioxide through the "incineration of some waste products that were made with fossil fuels, such as plastics and synthetic textiles." *Id.*

[28] 40 C.F.R. § 710.3; 40 C.F.R. § 704.3 ("Manufacture for commercial purposes also applies to substances that are produced coincidentally during the manufacture, processing, use, or disposal of another substance or mixture, including both byproducts that are separated from that other substance or mixture and impurities that remain in that substance or mixture. Such byproducts and impurities may, or may not, in themselves have commercial value. They are nonetheless produced for the purpose of obtaining a commercial advantage since they are part of the manufacture of a chemical product for a commercial purpose.").

[29] 44 Fed. Reg. 31525 (May 31, 1979); 40 C.F.R. § 761.

[30] *See, e.g.,* 40 C.F.R. Part 761.

[31] 40 C.F.R. § 761.3.

[32] 45 Fed. Reg. 592 (March 11, 1980);40 C.F.R. § 775 (1980) (prohibiting disposal of 2,3,7,8-tetracholorodibenzo-p-dioxin (TCDD) a manufacturing waste).

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Further, CO_2 emissions are in commerce as they are traded, bought, and sold as carbon offsets. CO_2 is also produced for commerical purposes including for uses in fertilizer, beverage carbonation, dry ice, refrigeration, pressurization, fire extinguishment, and packaging.

B. EPA Should Initiate Rulemaking to Control CO_2 under TSCA

Petitioners request that EPA make finding that CO_2 presents or will present an unreasonable risk of injury to the environment or health. TSCA requires that EPA "shall" initiate rulemaking upon finding "a reasonable basis to conclude that the manufacture, processing, distribution in commerce, use or disposal of a chemical substance of mixture … presents or will present an unreasonable risk of injury to health or the environment."[33]

The information and supporting documents provided in this petition indicate that CO_2 is already causing injury to the environment due to ocean acidification. The scientific evidence further supports that the injury to the environment and health will grow more severe as CO_2 pollution continues. EPA cannot deny that CO_2 is harming the environment. Indeed, EPA acknowledges that ocean acidification poses risk:

> Ocean acidification, like Climate change is primarily caused by increasing carbon dioxide (CO_2) concentrations in the atmosphere. As a result of absorbing large quantities of human made CO_2 emissions the ocean chemistry is changing, which is likely to negatively affect important marine ecosystems and species including coral reefs, shellfish, and fisheries.

(Environmental Protection Agency 2010).

EPA must find that such injury is an unreasonable risk.[34] While Congress did not define the phrase "unreasonable risk," EPA has interpreted relevant legislative history to require that the agency:

> balance the benefits derived from risk reduction against the social and economic costs incurred, taking into account such factors as the extent and magnitude of risk posed; the societal consequences of removing or restricting use of products; availability and potential hazards of substitutes; and impacts on industry, employment, and international trade.[35]

No specific factual determination is necessary to establish "unreasonable risk." For example, even under the stricter standard of 15 U.S.C. § 2606, EPA need not present evidence of actual injury before obtaining emergency injunctive relief to control "immanently hazardous chemical substance[s] or mixture[s]."[36] For the reasons discussed below, application of the agency's balancing test supports the additional regulation of CO_2.

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[33] 15 U.S.C. § 2605(a).
[34] *Id.*
[35] EPA, Guidance for Petitioning the Environmental Protection Agency Under Section 21 of the Toxic Substances Control Act, 50 Fed. Reg. 46,825 (Nov. 13, 1985).
[36] *See* H.R. Conf. Rep. No. 94-1679 78 (1976).

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According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013).

1. CO_2 Pollution Presents an Unreasonable Risk of Injury to the Environment

There is clear consensus among leading national and international scientific bodies that anthropogenic CO_2 causes changes in ocean chemistry that harm the marine environment. The Intergovernmental Panel on Climate Change ("IPCC") determined that human sources of CO_2 have caused a significant decline in surface ocean pH (Rhein et al. 2013), and over 90 national academies of sciences, including the United States', have signed a statement that ocean acidification will "cause grave harm to important marine ecosystems as CO_2 concentrations reach 450 ppm and above" (Interacademy Panel 2009). The Interacademy Panel concluded that CO_2 has increased ocean acidity with "potentially profound consequences for marine plants and animals" including severe threats to coral reefs, polar ecosystems, and a likely reduction in marine food supplies (*Id.*). The National Research Council also acknowledges that "existing data support a growing consensus in the research community that most documented responses to acidification reflect impairment of physiological capacity or performance" for marine life with likely substantial socioeconomic impacts (National Research Council 2013). The U.S. National Climate Assessment concluded that ocean acidification will alter marine ecosystems in dramatic ways including threatening coral reef habitats and causing reduced growth and survival of shellfish in all regions (Doney et al. 2014).

EPA acknowledges that "ocean acidification presents a suite of environmental changes that would likely negatively affect ocean ecosystems, fisheries, and other marine resources." 75 Fed. Reg. 13538 (Mar. 22, 2010). EPA previously concluded that greenhouse gases, including CO_2, endanger public health and the environment in part because of ocean acidification.[37]

There is no doubt that CO_2 pollution is changing ocean chemistry and harming the marine environment. Unabated, there will be severe and detrimental impacts on marine ecosystems, the economy, and public health. Accordingly, EPA must find that CO_2 poses an unreasonable risk to the environment and health.

a. CO_2 Causes Irreversible Ocean Acidification

Ocean acidification is a major threat to the marine environment. The oceans have absorbed CO_2 emitted into the atmosphere from power plants, manufacturing, cement production, and land use changes. Between 1750 and 2011, human activities have released 375 gigatons of carbon into the atmosphere, and approximately half of that has been absorbed by the oceans (Rhein et al. 2013). Each day about 22 million metric tons of CO_2 is taken up by the oceans (Feely et al. 2008). This uptake of CO_2 is changing ocean chemistry, causing the oceans to become more acidic. Since the industrial revolution surface ocean pH has declined by 0.11 units on average, corresponding with

[37] EPA, Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act 80 (Dec. 7, 2009).

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a 30% increase in acidity (Orr et al. 2005; Caldeira & Wickett 2005).[38] If emissions continue unabated, ocean acidity will increase up to 170% by the end of the century (IBGP et al. 2013).

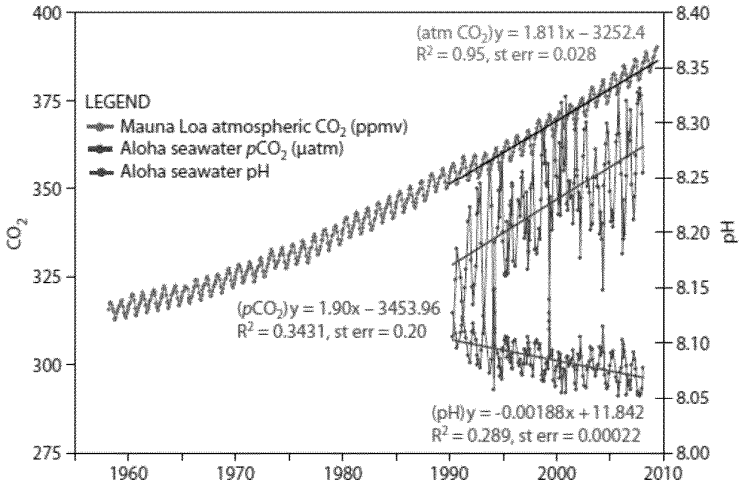

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the statistical limits of the measurements. (Feely et al. 2009).

Anthropogenic ocean acidification exceeds the trend in natural variability significantly, up to 30 times in some regions (Friedrich et al. 2012). The rate of change in ocean acidity is unprecedented in the past 300 million years, a period that includes four mass extinctions (Honisch et al. 2012; Zeebe 2012). The seawater chemistry change is an order of magnitude faster than what occurred 55 million years ago during Paleocene-Eocene Thermal Maximum, which is considered to be the closest analogue to the present, and during that period 96% of marine species went extinct (*Id.*). The current changes in seawater chemistry are irreversible on human timescales (Royal Society 2005).

CO_2's impact on ocean chemistry is fundamentally altering the marine environment with negative impacts on marine species, habitats and ecosystems.

i. What Is Ocean Acidification

When the ocean absorbs CO_2 from the atmosphere it changes ocean chemistry. CO_2 that is absorbed by seawater reacts to form carbonic acid, which dissociates to form bicarbonate and releases hydrogen ions. This reaction reduces the amount of carbonate ions and decreases pH. The oceans store a significant amount of the CO_2 pollution from human activities (Royal Society 2005). While this has provided society with an important service of buffering against climate change impacts, it comes at a cost to the marine environment.

[38] Because the pH scale is logarithmic a small decrease is a significant change in acidity; for example, a decrease of 0.1 pH is an approximate 30 percent increase in acidity.

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Globally, surface water pH has declined 0.11 units on average between 1750 and 1994 (Sabine et al. 2004). Long-term monitoring has documented the impact of increasing atmospheric CO_2 on declining seawater pH in the Pacific and Atlantic Oceans (*see* Figure 2). Results from time-series stations in the North Atlantic and North Pacific show a decrease of about 0.002 pH per year (Rhein et al. 2013).

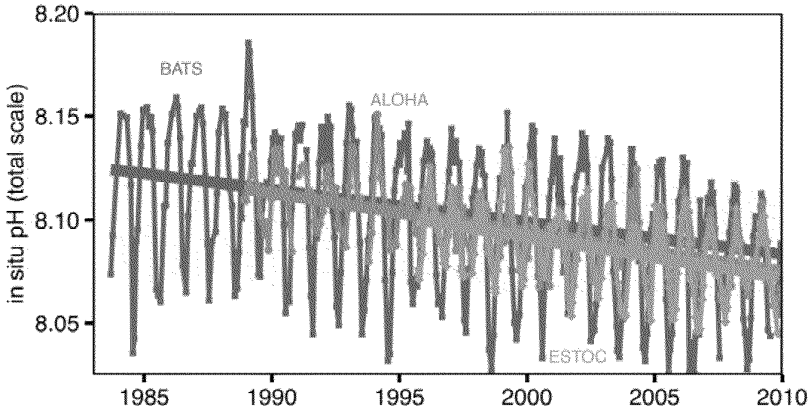

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (b) Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; orange) from 1988 to present (updated from Dore et al., 2009) and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; blue) from 1994 to present (updated from González-Dávila et al., 2010). Atmospheric pCO2 (black) from the Mauna Loa Observatory Hawaii is shown in the top panel. Lines show linear fits to the data, whereas Table 3.2 give results for harmonic fits to the data (updated from Orr, 2011).(Rhein et al. 2013)

Ocean acidification not only makes the oceans more acidic, but it also reduces the amount of carbonate ions available for animals to build the shells and skeletons they need to survive. Carbonate is an important constituent of seawater because many organisms form their shells and skeletons by complexing calcium and carbonate. Waters that are supersaturated with aragonite are generally good for shell-building, while undersaturated waters (<1.0 Ω_{ar}) are corrosive to some marine animals. Corals require supersaturated waters above 3.3 Ω_{ar} (Meissner et al. 2012). Globally, there has been a decrease of about -0.4 Ω_{ar} (Gruber et al. 2012). The aragonite saturation state has declined 16% since the Industrial Revolution due, in large part, to anthropogenic CO_2 (Feely et al. 2012a; Ishii et al. 2011). Modeling of the oceans' aragonite saturation predicts that by the end of the century up to 75% of ocean volume could be undersaturated with respect to aragonite (Joos et al. 2011).

ii. Observed and Predicted Acidification

CO_2 has already had measurable impacts on seawater chemistry. Some regions, such as those with upwelling systems or high latitudes, are especially vulnerable to ocean acidification.

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1. Pacific Coast

The West Coast is already experiencing adverse impacts of ocean acidification. As early as 2008, a survey off the coasts of Washington, Oregon, and California revealed that this region is already experiencing corrosive waters not expected until mid-century (See figure 3) (Feely 2008). Researchers found seawater undersaturated with respect to aragonite upwelling onto large portions of the continental shelf, reaching shallow depths of 40 to 120 meters (*Id.*). According to the study, the waters were last at the surface approximately 50 years ago when atmospheric CO_2 concentrations were much lower (Feely et al. 2008). Feely et al. report that in the Pacific Ocean there has been a decrease of the saturation state of surface seawater with respect to aragonite and calcite as well as an upward shoaling of the saturation horizon by about 1-2 meters per year on average, due in large part to anthropogenic CO_2 (R. A. Feely, Sabine, et al. 2012). As a result, marine organisms in surface waters, in the water column, and on the sea floor along the West Coast of the United States are already being exposed to corrosive water during the upwelling season.

Modeling of the California Current System demonstrates that the area is rapidly approaching year-round undersaturation with respect to aragonite and it is departing significantly from natural variability (Hauri et al. 2013). Time series monitoring shows that the aragonite saturation state along the California coast is much lower than would be expected in the North Pacific (Harris, DeGrandpre et al. 2013). Surface Ω_{ar} values ranged between 0.66 and 3.9 compared to an estimated pre-industrial range of 1.0 to 4.7. While some areas, like Puget Sound, already exhibit undersaturated conditions every year (Feely, Klinger, et al. 2012; Reum et al. 2014), scientists predict that most shallow shelf areas along the West Coast will become undersaturated with respect to aragonite within the next 20-30 years (Capone & Hutchins 2013; Gruber et al. 2012).

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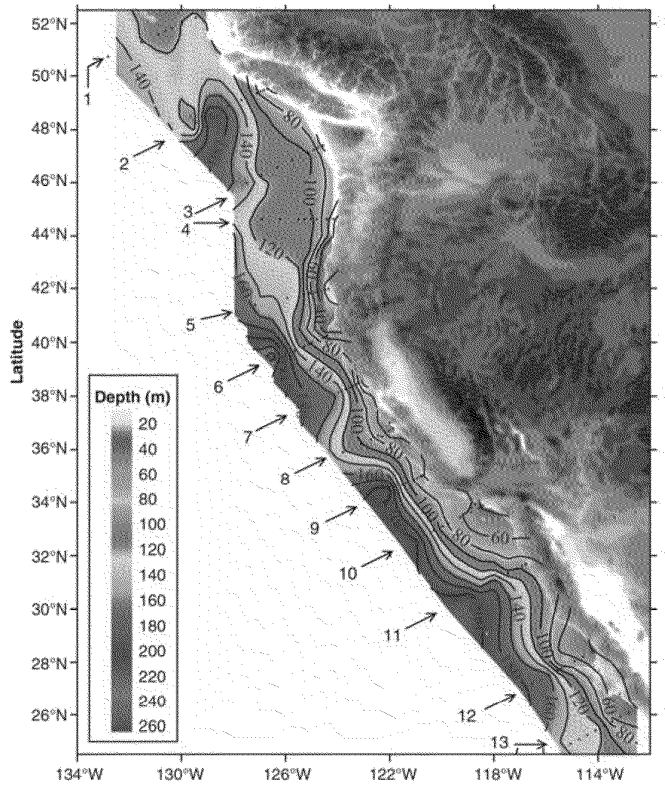

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al. 2008).

2. Alaskan Waters

High latitude waters are the "bellwether" of ocean acidification because these will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of greenhouse gas pollution (Fabry et al. 2009; Steinacher et al. 2009). High-latitude waters have naturally lower carbonate ion concentrations and saturation states due to a combination of cold temperatures which increase the solubility of CO_2 and ocean mixing patterns (Fabry et al. 2009; Mathis et al. 2011a). As early as 2016, 10% of Arctic surface waters are expected to be undersaturated with respect to aragonite for at least one month per year (Steinacher et al. 2009).

Recent observations of calcium carbonate saturation states in the North Pacific and Bering Sea have found that full water column undersaturation of calcium carbonate due to ocean acidification is already prevalent. Mathis et al. (2011a) reported that extensive areas of bottom waters over the Bering Sea shelf are becoming undersaturated with respect to aragonite for at least several months (July to September), and some areas of bottom water were already observed to be undersaturated with respect to calcite (Fabry et al. 2009, Mathis et al. 2011a).

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Scientists predict that polar waters will be corrosive to shellbuilding animals within decades (IBGP et al. 2013). A 2015 study of observations in the Chukchi and Beaufort Seas in the Arctic indicates that within 15 years waters will become so corrosive that it will be difficult for marine animals to build and maintain their shells (Mathis et al. 2015). The highly productive fisheries of Alaska are in some of the most rapidly changing seawater conditions (Mathis et al. 2014).

3. Sub-tropical Waters

Subtropical waters have experienced declining saturation states due to ocean acidification. Within decades, scientists believe that ocean acidification will impair coral growth (IBGP et al. 2013). Models show that by the end of the century, most coral reef areas will no longer have aragonite saturation states that are optimal for coral growth. A 10-year study of the Caribbean region found a strong regional decrease in aragonite saturation state between 1996-2006, from 4.05 to 3.9, resulting from CO_2 (Gledhill et al. 2008). Modeling predicts that under various emissions scenarios the coral reefs in the Caribbean will be thermally and chemically stressed between now and 2030 (Meissner et al. 2012). Even under the most optimistic scenario, 98% of reefs will be stressed by 2050 (*Id.*). In the Pacific subtropical ocean near Hawaii, there are nearly 20 years of time-series measurements of significant decreasing seawater pH that match the ocean's uptake of atmospheric CO_2 (Dore et al. 2009)

4. Atlantic Coast

Even ocean waters not at high latitude, in upwelling systems, or containing coral reefs ecosystems are, or will soon be, exhibiting signs of ocean acidification. Observations of East Coast waters during all seasons show that while they remain supersaturated with respect to aragonite, by the end of this century, saturation states of aragonite and calcite will decrease by 20–40%, with the lowest Ωar dropping to 1.3 in some seasons (Jiang et al. 2010). A survey of the Atlantic Coast showed that waters in the Northeast and particularly the Gulf of Maine are the most susceptible to ocean acidification (Wang 2013).

iii. CO_2 Kills and Injures Marine Life

High-CO_2 waters seriously harm marine wildlife and the entire ocean ecosystem. When CO_2 concentrations in seawater increase, the availability of carbonate ions decreases, making it more difficult for marine organisms to form, build, and maintain the calcium carbonate shells and skeletons required for their survival. As seawater becomes more corrosive, it can kill fish eggs and inhibit the development of, and essentially dissolve, the shells of small crustaceans, baby shellfish, and other tiny creatures at the base of the food web (Fabry 2008). Ocean acidification also harms and stresses fish, squid, and other animals that do not build shells (*Id.*). Not only does ocean acidification directly threaten various types of marine animals, it also has implications for the broader marine environment and food web.

The harmful effects of ocean acidification have already begun to occur. For example, ocean acidification has caused:

- A massive die-off of oysters in the Pacific Northwest (Barton et al. 2012; R. a. Feely, Sabine, et al. 2012; Washington State Blue Ribbon Panel 2012);

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- Declines in abundance and size of the California mussel, blue mussel and goose barnacle in tidepools correlated with a severely declining pH (Wootton et al. 2008);
- Sluggish growth of corals in the Caribbean and Great Barrier Reef (De'ath et al. 2009; De'ath et al. 2012; Gledhill et al. 2008); and
- Shells of plankton to dissolve off the California Coast and thinner and weaker shells of plankton in the Southern Ocean (Bednarsek 2014; Moy et al. 2009).

In a meta-analysis of over 400 experiments examining the impacts of ocean acidification on marine organisms, Kroeker et al. (2013) found the biological effects to be generally large and negative. This analysis was restricted to experiments with pH manipulations of less than 0.5 units, in order to reflect the predicted level of ocean acidification by the end of the century (IPCC 2007). By limiting the analysis to small variations in pH, this study shows that within the foreseeable future ocean acidification will have "profound repercussions for marine organisms" (Kroeker et al. 2010). While the negative effect of ocean acidification was most pronounced for calcification and survival (27% reductions in both responses), the study also revealed significant negative effects on growth and reproduction (11 to 19%, respectively). In addition, abundance was reduced by 15%. The strength of this analysis suggests that the patterns highlighted in this study are a robust representation of the current literature on ocean acidification.

While most of the worst consequences of ocean acidification are predicted for the future, scientists have already observed damage from CO_2 in the oceans. Additionally, the impacts of ocean acidification can affect the entire marine food web by altering habitat, prey availability, and species interactions.

b. High-CO_2 Waters Injure the Growth, Survival, Fitness, and Reproduction of Marine Animals

The primary known harm of CO_2 in the oceans is that it impairs the growth and survival of animals that build shells. Because ocean acidification reduces the availability of carbonate ions that marine animals use to calcify their shells and skeletons, CO_2 reduces the ability of these animals to build their protective structures (Doney et al. 2009). Acidified waters can also damage and dissolve shells.

These negative effects have been observed in the ocean as well as documented in laboratory studies. Corals, coralline algae, plankton, mollusks, and other shellfish exposed to future levels of ocean acidification have all experienced problems (Kleypas & Yates 2009; Kuffner et al. 2007; Barton et al. 2012; Talmage & Gobler 2011; Talmage & Gobler 2009; Orr et al. 2005; Riebesell et al. 2000).

i. Molluscs, Echinoderms, and Crustaceans

High CO_2 waters are lethal to shellfish. Since 2005, waters off the coast of Washington and Oregon have been killing oysters and other molluscs. Shellfish hatcheries in Washington and Oregon reported massive mortalities of oyster larvae (Washington State Blue Ribbon Panel 2012).Wild oysters also failed to reproduce in Willapa Bay, Washington (*Id.*). Scientists have definitively linked oyster production failures to high-CO_2 ocean waters that were used to raise larvae (Barton et al. 2012).

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In response to reported shellfish hatchery problems in Oregon, Barton et al. reported the results of their observations from the Whiskey Creek Hatchery on Netarts Bay in the summer of 2009 (Barton et al. 2012). Unlike previous laboratory experiments, this study analyzed calcifying organism responses in the ambient-water CO_2 chemistry of Oregon's coastal waters. Larval production and mid-stage growth (~120 um to ~150 um) of the oyster, *Crassostrea gigas*, were both significantly negatively correlated with the chemistry of waters in which larval oysters were spawned and reared for the first 48 hours of life. Although the impact of the exposure was not immediate, the delayed reaction caused a significant decline in growth for mid-sized oyster larvae and reduced overall production. The findings corroborate other laboratory studies that show that many marine species, especially at the larval stage, are adversely affected by ocean acidification.

Scientific studies have demonstrated that even modest pH declines affect the sensitive and vulnerable early developmental stages of organisms because these life histories have specific environmental needs (Kurihara 2008) (*see* Figure 10, below, showing negative effects from low pH treatments). A number of studies have found a delay in development or less development, degraded shells, decreased rate of metamorphosis, shell thickness, and loss of hinge integrity (Ross et al. 2011a). The resulting reduced larval size can reduce the feeding efficiency of larvae, and smaller larvae are more susceptible to starvation because they encounter comparatively less food (Kurihara & Shirayama 2004). Sub-lethal effects of elevated acidity can severely alter the composition and fitness of larvae, and given the high mortality rates of larvae in the water column and during the transition to benthic settler, small perturbations to larvae potentially may have large alterations to settlement dynamics, post-settlement mortality, recruitment, and ultimately adult populations (Ross et al. 2011).

Watson et al. (2009) exposed one day-old oyster larvae to a range of pH conditions, from 7.6 to 8.1, for 10 days and showed significant decline in the survival and growth of young larvae at lower pH. Waldbusser et al. (2010), in a study on the Chesapeake Bay, showed that even modest changes in pH present conditions that are corrosive to shells and have physiological impacts on adult and larval oysters. Biocalcification declined significantly with a reduction of 0.2 pH units, making juvenile bivalves more susceptible to predation and other mortality factors (*Id.*).

Negative effects have been seen on the metamorphosis, size, and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and Eastern oysters (*Crassostrea virginica*) at levels of CO_2 predicted to occur in the 21st century (Talmage & Gobler 2011). At 650 ppm, or an approximate drop of 0.3-0.4 from pre-industrial values, both *M. mercenaria* and *A. irrandians* larvae exhibited dramatic declines (over 50%) in survivorship as well as significantly delayed matamorphosis and significantly smaller size. *C. virginica* also experienced lowered growth and delayed metamorphosis at this level, an indicator that current and future increases in CO_2 populations may deplete or alter the composition of shellfish populations in coastal ecosystems (*Id.*).

The Olympia oyster, *Ostrea lurida*, a foundation species in estuaries along the Pacific coast, exhibits clear decline in larval growth and settlement as levels of CO_2 affect seawater pH. (Hettinger et al. 2012). Oysters in this experiment were raised at three levels of seawater pH,

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including a control (8.0) and two additional levels (7.9 and 7.8). Larvae reared under pH 7.8 exhibited a 15% decrease in larval shell growth rate, and a 7% decrease in shell area at settlement, compared to larvae reared under control conditions. Impacts were even more pronounced a week after settlement, with juveniles that had been reared as larvae under reduced pH exhibiting a 41% decrease in shell growth rate.

Oysters on the Atlantic coast also experience the ill effects of ocean acidification. Dickinson et al. (2012) found negative effects on juvenile eastern oysters after exposure to water with a 0.2 pH change. Exposure of the oysters to elevated acidity led to a significant increase in mortality, reduction of tissue energy stores and negative soft tissue growth, indicating energy deficiency. Under ocean acidification conditions, thermal tolerance is impaired in oyster larvae, leading to reduced development, size and increased abnormality (Ross et al. 2011; Parker et al. 2010). Similar results have been found in red abalone, with thermal tolerance impaired at pH 7.87 compared to control (pH 8.05) (Zippay and Hoffman 2010).

In studies with edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) researchers found a strong decline of calcification under ocean acidification conditions (Gazeau et al. 2007). Based upon these results, researchers concluded that mussel and oyster calcification may decrease by 25% and 10%, respectively, by the end of the century." (*Id.*). Oysters and mussels also exhibit development abnormalities when exposed to acidification (Kurihara 2008). When oyster eggs were reared under pH 7.8, they showed malformations of their shell, and when reared under pH 7.4, more than 70% of the larvae were either completely non-shelled, or only partially shelled, and only 4% of CO_2 treated embryos developed into normal larvae by 48 hours after fertilization, in contrast to about 70% successful development in control embryos.

The shrimp *Palaemon pacificus* displayed variable responses at different developmental stages, pH and length of exposure (Kurihara 2008). Following long term (30 weeks) exposure of adults to pH 7.89 and 7.64, survival and egg production in early developmental stages decreased in both treatments. Findlay et al. (2010) found a slower rate of development of embryos in the common intertidal northern hemisphere barnacle *Semibalanus balanoides* with an estimated 19 days delay in reaching 50% hatching stage at pH 7.7. Other amphipods have exhibited metabolic changes in response to acidification levels greater than what is allowed under the federal criterion (Hauton et al. 2009).

Echinoderms exhibit delayed and asymmetrical development when exposed to acidified conditions. In the absence of adequate adaptation or acclimation, lowered pH levels will have a range of sub-lethal effects on sea urchins, brittlestar and seastar larvae from a range of geographical regions (Ross et al. 2011). Larvae of the ecological keystone brittlestar, *Ophiothrix fragilis*, either were abnormal, had altered skeletal proportions, or asymmetry during skeletogenesis, and there was a delay in development at pH levels of 7.9, or approximately 0.3 units below current surface levels (Gutowska et al. 2009). Other experiments on brittlestar in low pH waters resulted in dramatic results; acidification of 0.2 units induced 100% larval mortality within an eight day period. Control larvae showed 70% survival over the same period. Because the calcite skeleton of the larval brittlestar aids key functions such as feeding and vertical migration, and defense against predators, abnormal development of the skeleton will have drastic consequences for fitness. The developmental abnormalities may be exacerbated by temperature

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increases predicted for the end of the century; some scientists suggest that this may result in the disappearance of echinoderms from the surface oceans within the next 50-100 years (Ross et al. 2011a).

Reproductive success is compromised by ocean acidification. The fertilization rate of sea urchins decreases with increasing CO_2 concentrations (8.1 to 6.8 pH) (Kurihara 2008). In another sea urchin experiment utilizing six CO_2 concentrations, with a pH between 8.01 (control) and 6.83, cleavage rate, developmental speed, and larval morphology all declined with increased CO_2 concentration (Kurihara & Shirayama 2004). At a 0.2 change from control, effects could be seen on the morphology and development of the larvae, and these effects became more pronounced with greater pH changes (*Id.*) (*see* Figure 4, below). The authors concluded that "all the effects of raised CO_2 concentration observed in this study would have a negative impact on the survival of sea urchin embryos in their early life history." A recent study showed that sea urchin sperm flagellar motility was significantly reduced when seawater pH decreased by .3 units, from 8.0 to 7.7 (Suwa et al. 2010). As discussed above, decreased flagellar motility has severe consequences for fertilization and subsequent population dynamics; if sperm lose their ability to find eggs, the population size will necessarily diminish.

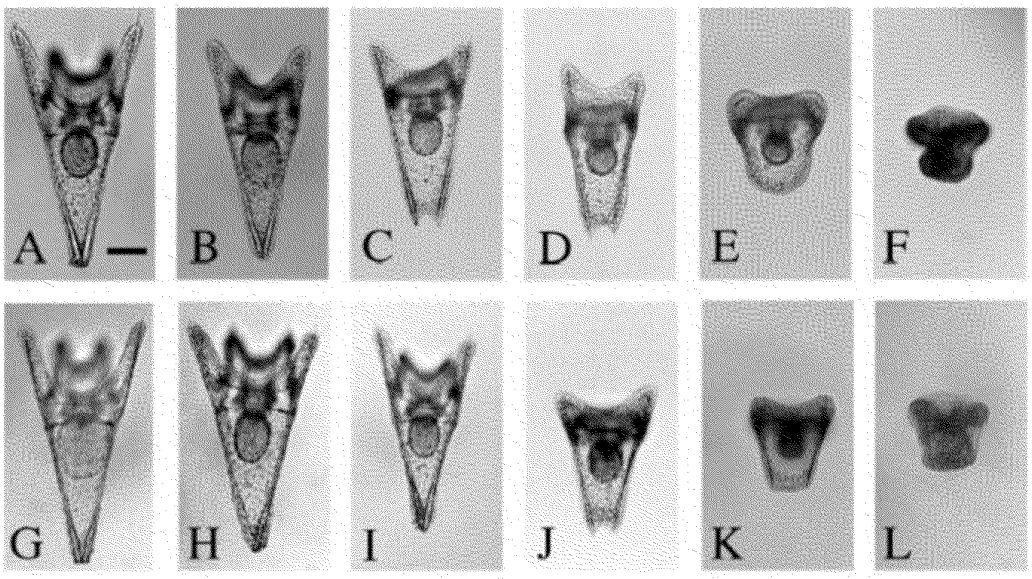

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8). Scale bar = 50 µm

Figure 4. Declining development of sea urchin larvae exposed to acidified waters (Kurihara & Shirayama 2004).

Even moderate increases in atmospheric CO_2 and ensuing acidification adversely affect the growth of both gastropods and sea urchins (Shirayama & Thornton 2005). Before the end of this century, atmospheric CO_2 is likely to increase by more than 200 ppm, decreasing the pH of the ocean by approximately 0.3 units from pre-industrial levels. Two species of sea urchin as well as the gastropod *Strombus luhanus* were exposed for six months to waters with this level of elevated CO_2, and all three species exhibited similar consequences. Increased CO_2 negatively affected growth rate, calcification, shell height and body mass, and metabolic activity

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(Shirayama & Thornton 2005). The developing embryos of the gastropod and intertidal snail *Littorina obtusata* also demonstrate slower overall development time, altered embryonic movement, and modification of shell shape in hatchlings while exposed to acidified waters (pH 7.6) (Ellis et al. 2009).

Arnold et al. (2009) investigated the effect of ocean acidification on lobsters and found that indirect disruption of calcification and carapace mass may adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function

Reduced metabolism is expected to impair predator-prey interactions, as well as have consequences for growth, reproduction, and survival. Metabolic suppression has previously been reported to occur in a variety of adult marine invertebrates, including crabs, squid, worms, bivalves, pteropods and amphipods (Albright 2011). Slowed metabolism is generally achieved by halting energy-expensive processes, such as protein synthesis, and therefore may lead to reductions in growth and reproductive potential (*Id.*). The blue mussel *Mytilus edulis* has strong physiological mechanisms by which it is able to protect body tissues against short-term exposure to acidified seawater, but these come at an energetic cost, and will result in reduced growth during long term exposures (Bibby et al. 2008). Consequently, the predicted long-term changes to sea water are likely to have a significant effect on the health and survival of blue mussel populations (*Id.*). Mussel beds are a dominant coastal habitat and provide food and structure for a diverse array of species in an otherwise physically stressful environment; any decline in their population structure will lead to a reduction in appropriate habitat for a myriad of other species.

In summary, acidified waters impact the development, growth, and reproductive success of a suite of echinoderms, crustaceans, and molluscs. A growing body of information is becoming available on the effecting of declining pH on these organisms and their ecosystems. The results of these studies are clear; as pH falls even 0.2 units from pre-industrial values, these organisms will struggle to survive in their increasingly acidic environment.

ii. Corals

Coral reef ecosystems, which are estimated to harbor one-third of marine species and which support the livelihoods of a half billion people, are particularly threatened by ocean acidification. Some corals are already experiencing reduced calcification (De'ath et al. 2009; Cooper et al. 2008; Bates et al. 2010; Gledhill et al. 2008). Due to the ocean acidification and warming, reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations of 450 ppm (Veron et al. 2009; Bijma et al. 2013). Prominent coral scientists have called for reducing atmospheric CO_2 to less than 350 ppm to protect coral reefs from collapse (Veron et al. 2009, Frieler et al. 2012). Coral reefs cannot exist below 7.8 pH units (Fabricius et al. 2011), and the threshold for coral growth is 3.3 Ω_{ar} (Meissner et al. 2012).

Ricke et al. (2013) analyzed aragonite saturation state (Ω_{ar}) surrounding reefs in CMIP5 simulations under several representative concentration pathway (RCP) scenarios (Ricke et al. 2013). The study found that in preindustrial times, 99.9% of reefs adjacent to open ocean in the CMIP5 ensemble were located in regions with $\Omega a > 3.5$. Accordingly, the study used $\Omega a = 3.5$ as

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an upper bound viability threshold for corals, while also examining thresholds of $\Omega a = 3.25$ and 3. Under a business-as-usual scenario (RCP 8.5), every coral reef considered was projected to be surrounded by water with $\Omega_{ar} < 3$ by the end of the 21st century and the reefs' long-term fate was independent of their specific saturation threshold. Under scenarios with significant CO_2 emissions abatement, the Ω_{ar} threshold for reefs was critical to projecting their fate. The study concluded that the "results indicate that to maintain a majority of reefs surrounded by waters with $\Omega_{ar} > 3:5$ to the end of the century, very aggressive reductions in emissions are required."

Corals are among the ecosystems most threatened by ocean acidification. To date, most scientific investigations into the effects of ocean acidification on coral reefs have been related to the reefs' unique ability to produce voluminous amounts of calcium carbonate (Kleypas & Yates 2009). The persistence of carbonate structures on coral reefs is essential in providing habitats for a large number of species and maintaining the extraordinary biodiversity associated with these ecosystems. As a consequence of ocean acidification, the ability of marine calcifiers to produce calcium carbonate will decrease, resulting in a transition from a condition of net accretion to one of net erosion, with drastic consequences for the role and function of these ecosystems (Kleypas & Yates 2009).

Coral reefs are predicted to drastically lower their calcification rates in the near future, and historical records show that calcification rates have already fallen relative to pre-industrial values. According to scientists, the main reef building organisms will calcify up to 50% less relative to pre-industrial rates by the middle of this century (*Id.*). A drop of approximately 60% coral reef calcification is projected for the end of the century, when pH is predicted to fall 0.5 units below pre-industrial values (Caldeira & Archer 2007). Many studies suggest calcification rates could be reduced between 20-60% at 560ppm, or 7.9 pH, and that a reduction of this magnitude would fundamentally alter reef structure and function (Convention on Biological Diversity 2009). According to the model of Silverman et al. (2009), developed from field observations from more than 9,000 reef locations, all coral reefs are expected to reduce calcification by more than 80% relative to their pre-industrial rate at 560 ppm (0.3 pH change), and at this point "all coral reefs will cease to grow and start to dissolve." The Interacademy Panel on International Issues concurs; "at current emission rates models suggest that all coral reefs and polar ecosystems will be severely affected by 2050 or potentially even earlier."

In a meta-analysis on coral calcification responses to ocean acidification, the coral calcification declined by a mean of 15% per unit decrease in aragonite saturation state ($2 < \Omega < 4$) (Chan and Connolly 2013). On current emission trends, calcification will decline 22% on average for corals by the end of the century (*Id.*). This falls to the lower range of responses that have been predicted by ocean acidification researchers and described above, which the authors believe reflects variation in the calcification responses of different corals.

Calcification rates at coral reef locations in the western tropical Pacific and the Caribbean may have already declined by 15%, (Caldeira & Archer 2007), and data from the Great Barrier Reef indicates a 14% decline in calcification rates between 1990 and 2005 (De'ath et al. 2009). Other studies in the Great Barrier reef indicate a decline of approximately 21%, and analysis of coral growth records confirm that this decline is unprecedented in recent centuries (Cooper et al. 2008). A model based on field samples shows that calcification of coral reefs in French

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Polynesia declined 15% between the pre-industrial period and 1992, and that rates will decline 40% by 2050, when CO_2 levels reach 560 ppm (pH 7.9) (Anthony et al. 2011). Near Bermuda, historical records show that coral skeletal density has decreased 33%, and coral calcification rates have declined by 52% as a result of changes in seawater carbonate chemistry (Bates et al. 2010). These observed changes have occurred even before a 0.2 unit decline in ocean pH; as atmospheric CO_2 continues to rise and lower pH values, calcification rates will maintain their precipitous decline.

Ocean acidification acts in concert with ocean warming and coral bleaching in furthering coral reef decline (Anlauf et al. 2011) (observing a 3% reduction in acidification with a 0.2 decline in pH, and a 30% decline when acidification is coupled with 1° C warming). While natural variability in the annual cycle and interannual variability may account for some of the observed change in coral growth rates, scientists are "virtually certain" that anthropogenic trends already exceed natural variability (Friedrich et al. 2012). Studies projecting the combined impacts of ocean acidification and ocean warming on corals predict that coral erosion will exceed calcification rates at atmospheric CO_2 concentrations of 450 to 500 ppm, (Hoegh-Guldberg et al. 2007), and all coral reefs will begin dissolve at CO_2 concentrations of 560 ppm (Silverman et al. 2009). These figures correspond to a 0.2 and 0.3 unit drop in pH, respectively, as compared to pre-industrial values. Van Hooidonk et al. (2014) presented updated global projections for threats to coral reefs from ocean warming and ocean acidification based on ensembles of IPCC AR5 climate models using the Representative Concentration Pathways (RCPs). For all tropical reef locations, the study projected absolute and percentage changes in aragonite saturation state (Ω_{ar}) for the period between 2006 and the onset of annual severe bleaching.

In the Caribbean, a recent study concluded that "coral reef communities are likely to be essentially gone from substantial parts of the Southeast Caribbean by the year 2035" (Buddemeier et al. 2011). The Great Barrier Reef has lost 50% of its coral cover since 1985 as a result of the combined effects of ocean acidification, global warming, coral bleaching, coral predation by starfish, and cyclone damage (De'ath et al. 2012). In short, due to the synergistic impacts of ocean acidification, mass bleaching, and local impacts, coral reefs are projected to experience "rapid and terminal" declines worldwide at atmospheric CO_2 concentrations 450 ppm, or pH 8.0, a level that is expected before mid-century (Veron et al. 2009).

Many experimental studies show declining calcification rates and other ill effects when corals are exposed to acidified waters. Decreases in calcification rates across a suite of benthic species and calcifying systems range from 3 to 60% for a doubling in pCO_2, which corresponds to a 0.3 reduction in pH (Abbasi & Abbasi 2011). The average response of corals is a 30% decline in calcification in response to a doubling in pCO_2 (*Id.*). In a study of an assemblage of corals exposed to conditions designed to mimic the change that may be experienced in the next 50-100 years (pH decline of 0.22 to 0.28 units), calcification rates declined between 44% and 80%.

The coral *Acropora palmata* (listed as threatened under the Endangered Species Act), once the dominant reef building coral in the Caribbean, experiences impaired fertilization, settlement, and growth with increasing pCO_2 (Albright et al. 2010). The cumulative impact of ocean acidification on fertilization and settlement success is an estimated 52% and 73% reduction in the number of larval settlers on the reef under pCO_2 conditions projected for the middle and end

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of this century, respectively (0.2 and 0.5 decline in pH) (*Id.*). After only 8 days of high CO_2 conditions (pH 7.75), *Acropora* experiences a statistically significant (18%) reduction in calcification rate (Murubini et al. 2003). Furthermore, there 22 coral species listed as threatened under the Endangered Species Act primarily because of threats from ocean warming, acidification and disease. The rule proposing listing for the corals found that ocean acidification was one of the highest priority threats for corals:

> Ocean acidification has the potential to cause substantial reduction in coral calcification and reef cementation. Further, ocean acidification adversely affects adult growth rates and fecundity, fertilization, pelagic planula settlement, polyp development, and juvenile growth.

77 Fed. Reg. at 73230 (Dec. 7, 2012). In other words, ocean acidification is driving the extinction of corals and the destruction of coral reef ecosystems.

Experimental studies evaluating the effects of ocean acidification on early life history stages of corals generally conclude that primary polyp growth is hindered by increasing acidity (Albright et al. 2010, Cohen & Holcomb 2009). Renegar and Riegl (2005) showed a significant decrease in the growth rate of *Acropora cervicornis* larvae at pH levels 0.3-0.5 units below control. Larvae of the common Atlantic golf ball coral, *Favia fragum*, shows significant delays in both the initiation of calcification and subsequent growth of the primary corallite in acidic waters (8.17 – 7.54 pH) (Cohen & Holcomb 2009). Visible changes in the skeletal development were observed in all non-control treatments, and in the most acidic waters skeletal development was 75% less than the control.

Acidification also affects cold water corals. Cold water corals have a worldwide but patchy distribution, and are often found in areas with highly productive fisheries (De Mol et al. 2002; Kenyon et al. 2003). Overall, more than two-thirds of all known coral species are cold water corals (Roberts & Hirshfield 2012; Cairns 2007). Recent exploration and research that has begun to search for, map, and observe cold water corals has found that these organisms are fragile, long-lived, slow-growing, very sensitive to physical or environmental disturbance and adapted for a specific environmental niche (McDonough & Puglise 2003). Alaskan waters are already showing widespread evidence of ocean acidification as a result of greenhouse gas emissions (Mathis et al. 2011a). By 2100, 70% of cold-water corals will be exposed to corrosive waters (Convention on Biological Diversity 2009). Conditions in waters typically inhabited by cold-water corals are even less favorable for calcification than those experienced by warm water corals; this may cause cold-water corals to be affected earlier and more strongly by CO_2-related ocean acidification than their warm water counterparts (Abbasi & Abbasi 2011).

The vulnerable early developmental and reproductive stages of cold water corals may be especially strongly impacted (Kurihara 2008; Dupont & Thorndyke 2009; Kroeker et al. 2010). In an experiment on the cold-water coral *Lophelia pertusa*, lowering the pH by 0.3 units relative to the ambient level resulted in calcification being reduced by 56% (Maier et al. 2009). Lower pH reduced calcification more in fast growing, young polyps (59% reduction) than in older polyps (40% reduction). Thus, corals' larvae and young corals are significantly more susceptible to ocean acidification than adults, and will likely show a higher degree of reduced calcification

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and growth with reduced pH, making young and larval corals less likely to survive to maturity as the ocean continues to absorb anthropogenic CO_2 and as climate change progresses.

In addition to reduced calcification rates, the strength of cementation may also be reduced in waters with a lower pH, promoting higher rates of physical and bio-erosion (Manzello et al. 2008). Once coral reefs experience lowered calcification and poor cementation, erosion and reef flattening can result, which severely reduced the structural heterogeneity of reefs and lowers its potential to support biodiversity. An important new study of reef bioerosion determined that the combined effects of lower calcification with increased bioerosion can significantly degrade coral reefs (Wissshak et al. 2012). In the study, a common bioeroding sponge in the Great Barrier Reef was observed on massive Porites. The sponge was more effective at bioerosion of the corals at high CO_2, ranging from 17% increase from present day levels to 61% increase at the highest CO_2 treatment. The researchers describe the important role of balancing the antagonistic processes of calcification and bioerosion in a reef for a healthy coral ecosystem, and predict detrimental consequences under ocean acidification as calcification declines and bioerosion increases.

Bioerosion may result in a loss of change in fish assemblages, lower densities of commercially important species, and lower rates of larval fish recruitment (Feary et al. 2007). Weaker reef calcification and cementation also increases the potential for reef damage as storm frequency and intensity increases with continued global warning, leading to further reef degradation (*Id.*). In a study looking at the impacts of storm damage and ocean acidification, researchers concluded that table coral populations are vulnerable to collapse (Madin et al. 2012). In the Indo-Pacific, table corals provide an important role in the reef ecosystem by creating reef structure and sheltering other reef species. They are also particularly vulnerable to ocean acidification, thermal stress, bleaching, disease and stress from storm waves. The table corals will become more vulnerable to storm waves as ocean acidification reduces calcification and increases bioerosion, therefore weakening their cementation and structure. Madin et al. (2012) found that a coral colony was four times more likely to be dislodged by a storm wave by the end of the century ocean acidification levels. Because of this vulnerability, the results showed that table corals are prone to large and rapid declines in coral cover.

Numerous biological responses independent of calcification are also negatively impacted by ocean acidification. Corals in acidifying waters are likely to be in a nutritionally or energetically stressed state and thus less likely to initiate reproduction, or successfully reproduce, due to negative impacts of ocean acidification on all stages of the reproductive cycle (Maier et al. 2009; McCulloch et al. 2012). Sperm flagellar motility also declines in response to decreasing pH. If sperm lose their ability to find eggs in the vast extent of the sea, the life of marine organisms is potentially limited. Sperm flagellar motility, which is indispensable for fertilization, is regulated by an elevation of intracellular sperm pH (Morita et al. 2010). While 69% of *Acropora* sperm were motile at pH 8.0, 46% were motile at pH 7.8, and fewer than 20% at pH 7.7 (*Id.*). Additionally, the physiological costs associated with reproduction are more likely to result in the demise of the organism due to the compounding stressors from ocean acidification and climate change (Wood et al. 2008, Cohen & Holcomb 2009). Significant reductions in metabolism have been observed for coral larvae following exposure to waters with a 0.2 decline in pH, levels projected to occur by the middle of this century (Albright & Langdon 2011).

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Albright et al. (2010) concluded that with increased CO_2 concentrations to those projected to occur in this century (560 atm to 800 atm, or a 0.3 to 0.5 decline in pH from pre-industrial values), the fertilization success of the tropical reef-building coral *Acropora palmata* decreased by 12-13%, settlement success reduced 45-69%, and linear extension was significantly reduced. The compounding effect of these impacts translated to 52-73% reduction in the number of larval settlers on the reef. Albright et al. (2010) predicted that the net impact on recruitment would actually be greater than that given that the depressed post-settlement growth is likely to result in elevated rates of post-settlement mortality. This corroborates other studies showing negative impacts on early-stage tropical corals.

Albright and Langdon (2011) tested the effects of ocean acidification on sexual recruitment of tropical corals. Larval metabolism was depressed by 27% at acidification levels expected by mid-century (0.3 pH reduction) and 63% at end-of-century acidification levels (0.4-0.5 pH reduction). Settlement was also reduced 42-45% and 55-60% at the mid and end-of-century levels respectively, relative to controls (Albright & Langdon 2011). Another study of larvae of tropical corals showed that short-term or long term exposure of larvae to ocean acidification decreased their metamorphosis (Suwa et al. 2010). This means that even when larval survivorship is unchanged, the success of recruiting new corals could be inhibited by ocean acidification (*Id.*).

Additionally, under conditions of acidification planktonic larvae lose their preference for settlement on the optimal crustose coralline algae communities (Doropoulos et al. 2012). Crustose coralline algae in turn, will experience a lower recruitment rate as marine waters become more acidic. Crustose coralline algae, a red calcifying algae, is of key importance in coral reef ecosystems, stabilizing reef structures and providing an important food source for benthic organisms (Convention on Biological Diversity 2009). Crustose coralline algae form a major calcifying component of the marine benthos from polar to tropical regions and are considered to influence the settlement of coral recruits. With a mean pH change of 0.26 between control and treatment, Kuffner et al. (2007) found that crustose coralline algae growth rates declined by 40%, and recruitment rate and percentage cover decreased by 78% and 92%, respectively.

In sum, reproduction is critical to maintaining a healthy coral reef population, and the long-term impacts of ocean acidification on reproduction, especially on larval settlement and growth, may significantly reduce the corals' ability to recover or maintain a population in the face of human caused disturbances and anthropogenic CO_2 emissions. This would result in a lack of reproductive capacity, genetic bottlenecks, and population collapse (Dupont et al. 2010; Ross et al. 2011).

As the world's oceans become more acidic and less saturated with carbonate minerals, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al. 2006). As coral skeletons weaken, they will become increasingly at risk of storm damage and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al. 2007). At greater than 550 ppm, coral reef ecosystems will be reduced to "crumbling

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frameworks." (*Id.*). Extensive studies have demonstrated that small changes in ocean chemistry will cause a suite of negative impacts, from reduced calcification rates to lowered reproductive success.

iii. Plankton

Plankton, which comprise the basis of the marine food web, are among the calcifying organisms adversely affected by ocean acidification. Changes to calcifying zooplankton, such as pteropods and foraminfera, have the potential to affect the ecological and tropic dynamics which govern the exchange of energy and cycling of nutrients throughout the marine food web (Gattuso & Hansson 2011). For example, the shelled pteropod, *Limacina helicina*, an Arctic pelagic mollusc, is a food source for higher predators such as fishes, whales and birds that are particularly important in high latitude areas. *L. helicina* makes up about 60 percent of the pink salmon diet (Comeau et al. 2012). A decline of pteropod population would likely cause dramatic changes to various pelagic ecosystems, and impact the commercially important salmon fishery; a 10% decrease in pteropods can lead to a 20% reduction in pink salmon body weight (Aydin 2005).

Pteropods form integral components of food webs, and are considered an overall indicator of ecosystem health (Orr et al. 2005). Studies have shown that pteropods exposed to a pH value predicted for the end of this century exhibited a 28% decrease in calcification (Comeau et al. 2009). Experiments on *L. helicina* showed that changes from 8.05 pH to 7.89 pH (Δ -0.16 units) cased shell dissolution and cracks appeared at 7.76pH, and linear extension of the shell decreased as a function of declining pH (Comeau et al. 2012). Samples show dissolution already happening in areas that have low aragonite saturation states. A sampling study off the coasts of California, Oregon, and Washington showed average to severe dissolution of *L. helicina* for 53% of onshore individuals and 24% of offshore individuals (Bednarsek 2014). A sampling study in 2008 of the Southern Ocean found severe dissolution of *L. helicina* in Ω_{ara} 1.0 (Bednarsek 2012). Another study found shell weights of one form of Antarctic species declined 35% from 1997-2006 (Roberts unpublished).

Ample studies corroborate that high CO_2 waters dissolve the shells of *L. helicina* and reduce calcification rates. Comeau et al. (2010) noted decreased calcification for *L. helicina* with decrease in aragonite saturation. Lishka (2012) looked at overwintering *L. helicina* and L. retroversa in the Arctic and noted that they do not calcify in the winter, and they are subject to dissolution under high CO_2 conditions. Bednarsek (2012) looked at *L. helicina* and *Clio pyramidata* from the Southern Ocean under different aragonite saturation states and recorded dissolution stages.

Modeling by Comeau et al. (2012) shows that by the end of the century *Limacina helicina* will not be able to calcify over much of the Arctic because of aragonite undersaturation—prediction may be conservative because it did not account for shell dissolution. Commentary suggests that as waters warm these pteropods will be trapped in acidified conditions and will "disappear entirely by the end of the century." Modeling suggests that waters in the California Current will be undersaturated year-round by 2050 (Gruber 2012). Modeling of the Arctic suggests that by mid-century the Bering Sea will be persistently undersaturated with respect to aragonite (Mathis 2011). An analysis of survey measurements in 2005-2006 and 1991-1992 demonstrated a

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shoaling of the aragonite saturation state in waters off Alaska (Feely et al. 2012). In the North Pacific the aragonite saturation state shoaled to depths less than 200 m between 40˚N and 50˚N (*Id.*). On average, the calcite saturation horizon in the Pacific shoaled about 1 m/yr from 1991 to 2006 (*Id.*).

Other species of plankton are also harmed by CO_2. Another pteropod, *Clio pyramidata,* kept in aragonite undersaturated waters began to dissolve within two days (Orr et al. 2005). Some coccolithophorids are also susceptible to ocean acidification. Studies showed that CO_2 related changes to seawater caused reduced calcification, resulting in malformed and incomplete shells. Calcification of cocolithophorids declined 15-44%, and their shells were malformed as pH changed up to about 0.3 units (Riebesell et al. 2000). Coccolithophorids are globally distributed and bloom in massive areas affecting the optical properties of the ocean, reflecting light from the earth, and play a major role in the ocean carbon cycle. Elevated CO_2 concentrations also reduce the shell mass of foraminifera (Kleypas et al. 2006). Modern shell weights of foraminifera in the Southern Ocean are 30–35% lower than those from preindustrial sediments, which is consistent with reduced calcification induced by ocean acidification (Moy et al. 2009).

iv. Cephlopods and Fish

The negative physiological effects of ocean acidification are not confined to invertebrates. For example, the gametes, embryos, and larvae of vertebrates such as fish are vulnerable to changes in ocean chemistry and have shown impairments in their homing and predator/prey detection capabilities.

Changes in the ocean's CO_2 concentration result in accumulation of CO_2 in the tissues and fluids of fish and other marine animals, called hypercapnia, and increased acidity in the body fluids, called acidosis. These impacts can cause a variety of problems for marine animals, including difficulties with acid-base regulation, calcification, growth, respiration, energy turnover, predation response, and mode of metabolism (Pörtner et al. 2005; Pörtner et al. 2004). Studies have shown adverse impacts in squid and fish, among other animals (Rosa & Seibel 2008; Ishimatsu et al. 2004; Pörtner et al. 2004). For example, when exposed to acidification, orange clownfish suffer a type of brain malfunction that interferes with their homing abilities and makes them 5-9 times more likely to swim toward a predator (Munday et al. 2009; Simpson et al. 2011; Ferrari et al. 2011).

Laboratory experiments have shown that ocean acidification at levels expected to occur within this century impairs larval orange clownfish and damselfish sensory abilities and behavior, making it more difficult for them to locate suitable settlement sites on reef habitat and avoid predators. Specifically, ocean acidification disrupts smell, hearing, and behavior of larval orange clownfish, (Munday et al. 2009; Nilsson et al. 2012), making larval clownfish attracted to odors from predators and unfavorable habitat (Munday et al. 2010; Dickson et al. 2010). Olfactory cues that prompted avoidance or neutral behavior in controls (pH 8.15) stimulated strong preference behavior in larvae raised at pH 7.8, in addition to significant reduction in response to usually positive preferences. Ocean acidification also impairs the hearing capacity of larval clownfish, which is predicted to have negative effects on settlement success and survival (Simpson et al. 2011).

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Similarly, research on six damselfish species found that ocean acidification impairs larval damselfish smell, vision, learning, behavior, and brain function, leading to higher risk of mortality. For example, in acidified waters, larval damselfish (1) become attracted to predator odors and display much riskier behaviors, making them more prone to predation; two species suffered a five-fold to nine-fold increase in predation rate at CO_2 levels of 700 to 850 ppm, or 0.3 pH units below control (Munday et al. 2009; Ferrari et al. 2011); (2) cannot discriminate between habitat olfactory cues, making it more difficult to locate appropriate settlement habitat (Devine et al. 2011); (3) settle on the reef during dangerous times—the full moon rather than new moon—when they are more vulnerable to predation (Devine et al. 2011); (4) fail to visually recognize or evade important predator species; (5) cannot learn to respond appropriately to a common predator by watching other fish react or by smelling injured fish, unlike fish under normal conditions (*Id.*); and (6) suffer disruption of an important neurotransmitter which is thought to result in the sensory and behavioral impairment observed in acidified conditions (Nilsson et al. 2012).

An animal's ability to transport oxygen is reduced by pH changes (Pörtner 2005). Water breathing animals have a limited capacity to compensate for changes in the acidity (Haugan 2006). For example, fish that take up oxygen and respire CO_2 through their gills are vulnerable because decreased pH can affect the respiratory gas exchange (Royal Society 2005). Changes in metabolic rate are caused by the changes in pH, carbonates, and CO_2 in marine animals (Haugan 2006).

Squid, for example, show a very high sensitivity to pH because of their energy intensive manner of swimming (Royal Society 2005). Because of their energy demand, even under a moderate 0.15 pH change squid have reduced capacity to carry oxygen and higher CO_2 pressures are likely to be lethal (Pörtner 2004). Even species more tolerant to pH changes experience decreased metabolism from increased CO_2 in the water (Pörtner 2004). For example, as much as 50% mortality was observed in copepods after only six days of exposure to waters with a pH level 0.2 units below the control (Pörtner 2005). Reducing pH by 0.3 pH cased a 31% decline in metabolic rate and a 45% decrease in activity level for the jumbo squid, an important predator in the Easter Pacific (Rosa & Seibel 2008).

In fish, pH also affects circulation. Fishexposed to high concentrations of CO_2 in seawater experience cardiac failure and increased mortality (Ishimatsu 2004). At lower concentrations sublethal effects can be expected that can seriously compromise the fitness of fish. Juvenile and larval stages of fish were found to be even more vulnerable (Ishimatsu 2004).

In sum, ocean acidification can have many adverse effects on marine animals that can reduce their fitness and survival (Royal Society 2005). Many marine animals have low thresholds for long-term CO_2 exposure (Pörtner 2005).

c. Other Environmental Impacts of Ocean Acidification

i. Increased Toxicity of Harmful Algal Blooms and Sediments

Ocean acidification may already be increasing the toxicity of harmful algal blooms known as "red tides." These toxic red tides poison shellfish, marine mammals, fish, and even cause

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paralytic shellfish poisoning in people. High CO_2 levels in seawater magnify the toxins of harmful algae. (Fu et al. 2012; Avery O Tatters et al. 2013; Tatters et al. 2012; Avery O. Tatters et al. 2013). Studies of the genus *Pseudo-nitzscia* show that the toxicity of diatoms which produce a neurotoxin increases significantly under ocean acidification conditions. A -0.5pH change caused toxin production in the diatoms to increase 4.2-fold and a -0.3pH unit change increased the toxicity 2.5-fold (Tatters et al. 2012). Many studies on the effects of ocean acidification and algal blooms have been conducted at CO_2 levels that are already occurring in California, and the increase in the toxicity of harmful algal blooms in Southern California (and resulting mass mortalities of fish and marine mammals) may be due, in part, to acidified waters (*Id.*) However, these studies suggest that the damage will become much worse.

Additionally, research shows that under conditions of ocean acidification sediments become more toxic (Roberts, Birchenough et al. 2013). Ocean acidification makes sediment-bound metals more available and thus more toxic for aquatic life (*Id.*) For example, ocean acidification increases the toxicity of copper (Campbell & Mangan 2014).

ii. Noise Pollution Increases in Low pH Waters

Ocean acidification can also decrease the sound absorption of seawater, causing sounds to travel further with potential impacts on marine mammals and other marine life sensitive to the sounds of vessel traffic, seismic surveys, and other noise pollution (Hester et al. 2008). Sound travels 10-15 percent further with a change of 0.1 pH, and it is predicted to increase about 40 percent by mid-century (Hester et al. 2008). Additionally, a decline of 0.3 pH units causes a 40 percent decrease in the sound absorption of surface seawater and sound may travel 70 percent farther, further affecting sensitive marine mammals (Brewer et al. 2009).

d. Ocean Acidification's Ecosystem Impacts

While the full implications of elevated CO_2 on marine ecosystems are not well-documented, there is high confidence that there will be negative ecosystem consequences from ocean acidification. The exact changes are difficult to predict, but some of the anticipated impacts include loss of diversity, loss of abundance of calcifying species, shifting prey and predator interactions, and loss of suitable habitat.

New mesocosm studies have sought to understand some of the potential ecosystem impacts of CO_2. Studies of biodiversity near underwater volcanic vents demonstrate reduced richness in high-CO_2 waters. For example, coral species diversity declined by about 39% between low and high-CO_2 sites, with the reefs shifting from complex communities to a coral reef dominated by massive Porites. Most importantly, the researchers found that coral reef development ceases at 7.7 pH, and they concluded that a pH decline below 7.8 would be "catastrophic for coral reefs" (Fabricius et al. 2011). Scientists also observed that in high-CO_2 waters the loss of complex coral reef habitat resulted in a loss of diversity of reef-associated species such as crustaceans and crinoids (Fabricius et al. 2014). Looking at the macroinvertebrates, the density declined 48% between control and high-CO_2 areas and taxa diversity declined by 77% (*Id.*).

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Loss of species diversity associated with ocean acidification can also result from changes in competitive interactions. A study of a rocky reef near volcanic vents documented that macro algae outcompeted calcareous species in low-pH waters (Kroeker et al. 2012). The researchers explained that under the high-CO_2 conditions the calcifying species grew more slowly while the seaweed took hold and that grazing of seaweed was depressed (*Id.*). In another study, while the areas near volcanic vents lacked scleractinian corals and had low abundance of sea urchins and coralline algae, invasive algal species benefited from the acidified conditions (Hall-Spencer et al. 2008).

Research on the diversity the intertidal community in the Pacific Northwest documented a shift from a ecosystem dominated by calcifying animals to one with non-calcifying organisms as pH declined. Researchers documented declines in abundance and size of the California mussel, blue mussel, and goose barnacle in tidepools on the Olympic Coast in Washington (Wootton et al. 2008). They found that in years with low pH waters the calcifying animals were replaced by non-calcifying organisms (*Id.*).

The synergistic impacts of ocean acidification and warming are also potentially severe. Ocean acidification may induce a negative climate feedback that may increase temperature rise. Mesocosm studies found that ocean acidification may amplify global warming through decreasing biogenic production of the marine sulfur component dimethylsulphide which can impact cloud albedo (Six 2013). Ocean acidification therefore may also contribute to climate change impacts on the environment.

2. Risk Reduction Costs and Benefits

EPA must make a determination whether the risk of ocean acidification is unreasonable and this constitutes a balancing of costs and benefits. While it is EPA's burden to conduct this analysis, petitioners present some limited data on (1) the socio-economic costs of CO_2 pollution in light of ocean acidification, (2) the feasibility of controls on CO_2 pollution, and (3) the social cost of carbon including the costs of delaying action to reduce and mitigate CO_2 pollution.

a. Socioeconomic Costs of Ocean Acidification

The release of CO_2 into the environment is already having social and economic impact, and these impacts are predicted to become even more concerning. Primary economic concerns are from the loss of fisheries and coral reefs. Ocean acidification also poses food security and nutrition risks.

U.N. Convention on Biological Diversity estimated costs on the predicted damage of ocean acidification and predicts that the oceans will lose more than $1 trillion in value annually from ocean acidification (Convention on Biological Diversity 2014). CO_2 related ocean warming and acidification will threaten marine food resources by disrupting marine communities, promoting harmful algal blooms and the spread of some diseases, and increasing contaminants in fish and shellfish (Tirado et al. 2010).

The United Nations Environment Programme reported that ocean acidification's impact on marine organisms is a threat to food security (UNEP 2010). The report documents that ocean

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acidification is measurable and increasing, which poses a threat to fisheries resources and the billions of people that have a marine-based diet (United Nations Environment Programme 2010). Seafood has been shown to prevent hundreds of thousands of premature deaths, as well as significantly reduce infant morbidity; a decline of seafood availability will decrease these benefits. Some populations, including subsistence fishing populations and poor communities, depend on seafood and mortality and morbidity can result from the loss of these food sources (Mozaffarian 2006). For example, 95% of Alaskan households do some sort of subsistence fishing, and 17% of the state's population, 120,000 people, depend on subsistence fishing (Mathis et al. 2014). Many subsistence fishers also have cultural ties threatened by ocean acidification. Accordingly, CO_2 can result in social and environmental justice concerns that must also be assessed and weighed (Convention on Biological Diversity 2014).

Not only will ocean acidification affect global food webs and ecosystems, it will have a direct effect on the global economy. The U.S. economy is very dependent on the health of the ocean. In 2009, the ocean economy contributed over $223 billion annually to the U.S. gross domestic product and provided more than 2.6 million jobs (NOAA, http://oceanservice.noaa.gov/facts/oceaneconomy.html). Cooley and Doney (2009) estimate that if just a 10-25% decrease in United States mollusk harvests from 2007 were to occur today, $75-187 million in direct revenue would be lost each year henceforth, with a net loss of $1.7-10 billion through mid-century, when pH levels are approximately 0.3 units below pre-industrial values. In Washington State alone, the seafood industry generates $1.7 billion for gross state product and employs 42,000 people (Washington State Blue Ribbon Panel 2012). Already, shellfish hatchery failures in Washington have caused an economic stir and caused some hatcheries to relocate. Alaska's commercial fishing industry is valued at over $4 billion a year, and supports 90,000 jobs—recreational fishing and fishing tourism add even more value. Meanwhile, Alaska is ranked among the most vulnerable areas to acidification.

Tropical coral reefs provide ecosystem services, such as habitat and nursery functions for commercial and recreational fisheries and coastal protection. As reefs decline in acidified waters, there will be an ecological shift to a new ecosystem state dominated by less commercially valuable species. In 2009, Brander et al. estimated the annual economic damage of ocean acidification-induced coral reef loss to escalate rapidly over time, reaching $870 billion by 2100 (Brander et al. 2009a). In 2014, Brander et al. increased the anticipated loss of ecosystem services from corals to be $1000 billion (UNEP 2014). Shoreline protection offered by coral reefs and the services it provides by preventing loss of life, property damage and erosion are also reduced by CO_2 emissions.

Lane et al. (2014) modeled three major U.S. locations for shallow water reefs -- South Florida, Puerto Rico, and Hawaii – to project future reef cover and the economic values generated by coral reefs for a greenhouse gas emissions mitigation scenario that represents international implementation of policies to reduce global emissions (resulting in a CO_2 concentration of 427 ppm in 2100), compared to a business as usual greenhouse gas emissions scenario resulting in a CO_2 concentration of 785 ppm in 2100. The study estimated that reducing emissions would result in an "avoided loss" in Hawaii of approximately $10.6 billion in recreational use values compared to business as usual. Reducing emissions was projected to provide fewer economic benefits in Puerto Rico and South Florida, where sea-surface temperatures are already close to

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bleaching thresholds and coral cover is projected to drop well below 5% cover under both scenarios by 2050, and below 1% cover under both scenarios by 2100 (Lane et al. 2014).

As discussed previously, the toxicity of harmful algal blooms increases under conditions of ocean acidification. These toxins not only poison marine mammals, but also cause paralytic shellfish poisoning in people. Scientists hypothesize that some of the increases red tides off the coast of Southern California may be related to ocean acidification, though this has yet to be confirmed. In turn, harmful algal blooms cost the United States approximately $82 million each year from impacts to fisheries, public health, management, and lost recreational opportunities (Hoagland and Scatasta 2006).

A recent study estimated that the damage our oceans will face from emissions-related problems will amount to $428 billion a year by 2050 and nearly $2 trillion per year by the century's end (Noone et al. 2012).

> Acidification impacts processes so fundamental to the overall structure and function of marine ecosystems that any significant changes could have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods.

(Doney et al. 2009). There is also a significant cost to delaying action. According to a recent report by the Council of Economic Advisers, delaying the implementation of policies to mitigate climate change could significantly increase economic damages, in addition to worsening environmental harm.[39]

While there are still large unknowns on the biological consequences of ocean acidification, the science we have is clear: from shellfish to corals, and from pteropods to fish, our marine resources are threatened by the acidification of our ocean waters.

b. Risk Reduction Methods

There are several ways to reduce risk from CO_2. EPA should use a suite of tools to reduce emissions, sequester CO_2, mitigate harms, and promote alternatives. Under TSCA EPA has authority to:[40]

- prohibit or limit the amount of production or distribution of a substance in commerce;
- prohibit or limit the production or distribution of a substance for a particular use;
- limit the volume or concentration of the chemical produced;
- prohibit or regulate the manner or method of commercial use;
- require warning labels and/or instructions on containers or products;
- require notification of the risk of injury to distributors and, to the extent possible, consumers;

[39] Executive Office of the President of the United States, The Cost of Delaying Action to Stem Climate Change at 1 (July 2014).
[40] 15 U.S.C. § 260.

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- require record-keeping by producers;
- specify disposal methods; and
- require replacement or repurchase of products already distributed.

EPA also may impose any of these requirements in combination or for a specific geographical region. [41] Specifically, the agency must impose controls sufficient "to protect adequately against such risk using the least burdensome requirement."[42]

There is evidence that many industries could employ existing technology to achieve meaningful emissions reductions affordably. EPA's own data demonstrate that lower pollution rates are readily achievable for many industrial sources of CO_2. For example, the agency has identified dozens of "control measures and energy efficiency options that are currently available for pulp and paper mill processes," ranging from technological upgrades to improved equipment maintenance.[43] Similarly, EPA has compiled more than a decade of reports on "cost-effective" control strategies and other approaches available to reduce cement plant CO_2 emissions, "includ[ing], for example, energy efficiency measures, reductions in cement clinker content, and raw materials substitution."[44]

Although cost-effective strategies to reduce CO_2 emissions are available, existing controls have not reduced CO_2 emissions sufficiently to protect against environmental harm. For example, most natural gas power plants have *never* exceeded the agency's recently proposed emissions limit, thus indicating that existing and newly constructed facilities could easily satisfy a more stringent standard.[45] Because energy-related CO_2 pollution accounts for more than eighty percent of U.S. greenhouse gas production, readily achievable reductions in this sector would significantly benefit the environment.[46] Similarly, the pulp and paper industry ranks among the largest consumers of energy,[47] and emitted nearly 58 million metric tons of CO_2 equivalent gases in 2004.[48] Moreover, market incentives and regulatory controls are effective in increasing the rate of innovation for technologies that can reduce CO_2 emissions.

If a chemical presenting an unreasonable risk to health and the environment has already been distributed, EPA may prescribe procedures by which relevant manufacturers and purchasers must replace or repurchase that chemical.[49] In the present situation, we urge the agency to exercise its

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[41] *Id.*
[42] 15 U.S.C. § 2605(a).
[43] *See* EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 11 (2010).
[44] EPA, National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants, 75 Fed. Reg. 54,970, 54,997 (Sep. 9, 2010).
[45] Ctr. for Biological Diversity, Comments on Standards of Performance for Greenhouse Gas Emissions from New Stationary Sources: Electric Utility Generating Units (Proposed Rule) Docket No. EPA-HQ-OAR-2013-0495 at 13-14 (May 9, 2014).
[46] U.S. Dept. of State, U.S. Climate Action Report at 16 (2010).
[47] *See* U.S. Energy Information Administration, First Use of Energy for All Purposes (Fuel and Nonfuel), 2010 (Mar. 2013), http://www.eia.gov/consumption/manufacturing/data/2010/#r1.
[48] EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Industry at 7 (2010).
[49] 15 U.S.C. § 2605(a)(7)(C).

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authority to remediate existing harm by requiring that responsible parties mitigate past CO_2 emissions.

There are numerous approaches to mitigating and sequestering CO_2 emissions that EPA must evaluate. Effective land use and agricultural practices can significantly reduce carbon emissions and sequester CO_2. Federal programs aimed at consumers can reduce CO_2 emissions. For example, EPA's Energy Star program has prevented 1.8 billion tons of greenhouse gas emissions by providing information that helps customers select energy efficient devices. Sequestration of CO_2 in products, infrastructure, and waste management are among numerous methods that could be cost-effective to mitigate CO_2 pollution.

c. Social Costs of Carbon

In any analysis of the cost and benefits of reducing CO_2 pollution, the costs of failing to address the problem of global warming should be included. Most efforts to quantify the social costs of carbon underestimate the real-world costs of CO_2 pollution. Nevertheless, EPA may not ignore these costs.

Global emissions must be less than 1000 Gt of CO_2 between 2000 and 2050 to avoid dangerous climate change, which scientists have recommended that this means maintaining temperature change below 2° C.[50] This means keeping atmospheric CO_2 to 450 ppm, a threshold below which experts also use for ocean acidification (Veron et al. 2009; Silverman et al. 2009; Interacademy Panel 2009; McNeil & Matear 2008; Sea et al. 2007). For example, coral scientists predict that at 450 ppm, reef-building will be severely diminished or will cease altogether (Veron et al. 2009). But the global community has already used a substantial portion of this CO_2 budget, emitting 305 Gt of CO_2 between 2000 and 2008 alone.[51] As a result, the years between now and 2020 have been dubbed the "critical decade."[52] Because carbon emissions must peak soon and decline thereafter, the sooner emissions peak, the less severe the subsequent annual reductions will need to be;[53] correspondingly, if emissions are not sufficiently curbed in this decade, avoiding catastrophic damages will require much more drastic, disruptive and costly measures and may no longer be possible at all. Nonetheless, if action is taken immediately, it is both technologically and economically feasible to reduce emissions by 2020 and lay the groundwork for future emissions reductions.[54]

Every year that the world delays its efforts to reach sustainable levels of greenhouse gas emissions represents a lost opportunity of tremendous economic significance. McKinsey & Company estimated in 2009 that for every year of delay, 1.8 Gt of potential CO_2 abatement is foregone.[55] This delay, and the accompanying Gts of lost CO_2 abatement, has a price tag, as the

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[50] Australia Department of Climate Change and Energy Efficiency, The Critical Decade: Climate Science, Risks and Responses at 53 (May 2011), *available at* http://www.scribd.com/doc/56043375/The-Critical-Decade-Climate-Change-Commision-Report.
[51] *Id.*
[52] *Id.*
[53] UNEP, The Emissions Gap Report at 14 (Nov. 2010), *available at* http://www.unep.org/publications/ebooks/emissionsgapreport/; for a discussion of economic implications of these facts, *see infra.*
[54] *Id.* at 23.
[55] McKinsey & Company, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve at 16 (2009), *available at* www.worldwildlife.org/climate/WWWFBinaryitem11334.pdf.

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damage caused by CO_2 emissions accelerate while the cumulative amount of greenhouse gases in the atmosphere rises, both because of the increasingly dire damages wrought by rising temperatures and other greenhouse gas effects, *and* because of the delay factor itself. If governments delay mitigation in the present, the emissions reduction curve in future years necessarily becomes much steeper, requiring much more drastic and costly emission reduction mechanisms with tremendous economy-wide disruptions, just to "catch up" with the lost opportunities from prior years to reach a sustainable emissions trajectory—or risk undergoing unsustainable climatic extremes.

Economists have sought to quantify the costs of waiting to embark upon an emissions reduction path. In 2007, researchers used the DICE model[56] to estimate the cost of delaying mitigation for a given period of time and then switching to an optimal abatement trajectory. According to their findings, the global cost of ten years of delay, relative to starting on an optimal trajectory in the present, ranges from hundreds of billions to several trillion dollars.[57] For instance, this study estimates that it would cost somewhere between $200 and $400 billion dollars to delay action for ten years and then embark upon a mitigation strategy that would result in stabilization at 3 °C (a level now universally understood to far exceed the dangerous). The cost of delaying mitigation soars into the trillions of dollars as the delay continues, until it ultimately becomes impossible to achieve a certain level of temperature stabilization. According to this study, more than thirty years' delay of changing the current course would make it impossible – no matter what the expense – to stabilize temperature rises at 2° C above pre-industrial levels.

EPA and other federal agencies have been using the social cost of carbon to estimate the climate benefits of rulemakings since it was first developed by a dozen agencies (including USDA, CEQ and EPA) and published by the Interagency Working Group in 2010.[58] The social cost of carbon, usually expressed as a dollar-per-ton figure, provides an estimate of the economic damages associated with an increase in CO_2 emissions, conventionally one metric ton, in a given year. The dollar figure can also represent the value of damages avoided for emission reductions achieved by federal rulemakings. The social cost of carbon is designed to provide a comprehensive estimate of climate change damages, including, but not limited to, changes in net agricultural productivity, human health, and property damages from increased flood risk. However, given current modeling and data limitations, even EPA has conceded that that the social cost of carbon protocol is likely a conservative estimate because it does not yet account for all important damages.[59] Nevertheless, the protocol is designed for use in regulatory processes like this one. In 2013 the Federal Interagency Working Group increased its estimates of the social cost of carbon, using the same 3% annual discount rate, by 50%.[60] The 2013 estimates are 50% higher for emissions in 2010, with greater percentage increases in subsequent years. Yet, even these social

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[56] DICE stands for the Dynamic Integrated Climate and Economy model developed by William Nordhaus in 1990.
[57] Keller, K. et al., The Regrets of Procrastination in Climate Policy, Environmental Research Letters (2007), *available at* iopscience.iop.org/1748-9326/2/2/024004/.
[58] EPA, The Social Cost of Carbon, http://www.epa.gov/climatechange/EPAactivities/economics/scc.html (last accessed June 28, 2015).
[59] *Id.*
[60] Interagency Working Group on Social Cost of Carbon, United States Government, Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 (Nov. 2013) at 3, available at http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-updatesocial-cost-of-carbon-for-regulator-impact-analysis.pdf.

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cost of carbon figures significantly underestimate the true social cost of carbon, possibly by several orders of magnitude.

Economists have noted that the social cost of carbon is far greater than the $21 per ton of CO_2 assumed by interagency protocol in 2010 and greater than the 2013 revision.[61] There are several inadequacies that make the values too conservative. Foremost, the models fail to evaluate ocean acidification—to the contrary the models consider the ocean a sink for CO_2. The FUND model used in the Working Group's analysis wholly excludes consideration of climate-induced catastrophic events. But the Working Group weighs the values generated by each of the three models equally, even though the FUND model's values is significantly lower[62] than the others, and consequently pulls down the final value of the social cost of carbon. The potential for catastrophic climate events, and the increasing likelihood that tipping points will be reached even sooner than anticipated, are increasingly serious risks, however, and, despite the associated uncertainties, must be fully represented in any evaluation of the social cost of carbon. Instead, the Working Group employed a risk-neutral approach, clearly inappropriate in light of the vast majority of scientific studies. Also, the models used fail to account fully or even partially for certain highly complex aspects of climate change, including the possibility of interrelations between different sectors and accelerating damage feedback loops, non-CO_2 emissions,[63] and social and political instability. Moreover, the valuation techniques and discount rates used to reach these values are inherently problematic and fail to represent the full value of all losses from climate change, in significant part because some cannot be reduced to monetary terms.

Other evaluations of the social cost of carbon attempt to account for these omitted factors. The Stern Review, in particular, reaches a SCC of $85/ton of CO_2 (in 2000 dollars).[64] For comparison purposes with a Working Group value of $21 in 2005 dollars, this amount is equivalent to

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[61] F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon (2010) (the social cost of carbon could be over $800 per ton of CO2 equivalent; F. Ackerman & E. Stanton, Climate Risks and Carbon Prices: Revising the Social Cost of Carbon, in Economics, vol. 6 (Apr. 4, 2012) (reaching similar conclusions), available online at http://www.economics-ejournal.org/economics/journalarticles/2012-10 (last visited June 27, 2014); P. Epstein et al., Full cost accounting for the life cycle of coal, Ann. N.Y. Acad. Sci. (2011) (estimating the social cost of coal at between $10 and $100 per ton of CO2 equivalent); L. Johnson & C. Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, J. Envtl. Stud. & Sci. (Sept. 9, 2012) (finding a social cost of a ton of CO2 emissions to be 2.6 to over 12 times larger than the Interagency Working Group's central estimate of $21 per ton of CO2) available online athttp://link.springer.com/article/10.1007%2Fs13412-012-0087-7 (last visited June 27, 2014) E. Stanton et al., Comments on the 2013 Technical Update of the Social Cost of Carbon, January 27, 2014.

[62] Interagency Working Group on the Social Cost of Carbon, Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, at 16-A-11, Fig. 16-A-4.2, *available at* http://www.rff.org/Publications/WPC/Pages/Estimating-the-Social-Cost-of-Carbon-for-Regulatory-Impact-Analysis.aspx.

[63] For instance, the estimated social cost of methane and SF_6, are, respectively, $105/tonne and $200,000/tonne. *See* Intergovernmental Panel on Climate Change, Climate Change 2007 Synthesis Report 822, *available at* http://www.ipcc.ch/publications_and_data/ar4/syr/en/contents.html. For a critical analysis of the Working Group's assumptions, *see also* Ackerman, F. and Stanton, E. A., The Social Cost of Carbon A Report for the Economics for Equity and the Environment Network (April 1, 2010), *available at* http://www.e3network.org/papers/SocialCostOfCarbon_SEI_20100401.pdf.

[64] Nicholas Stern, Stern Review on the Economics of Climate Change Part III: The Economics of Stabilisation at 287 (2006), *available at* http://webarchive.nationalarchives.gov.uk/+/http:/www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm.

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$96.25/ton in 2005. The Stern Review uses the PAGE model, which explicitly models for the risk of catastrophic climate change.[65] In contrast with the Working Group, the Stern Review uses a mean temperature increase of 3.9 °C for its baseline scenario (consistent with the Third IPCC Report) and a 4.3 °C increase for its higher climate scenario. The resulting higher value of the social cost of carbon is thus very likely to be a closer approximation of the real cost of CO_2.

Meanwhile, the costs of reducing CO_2 emissions are well worth taking prompt action. The "central estimates of the annual costs of achieving stabilisation between 500 and 550ppm CO_2 are around 1% of global GDP, if we start to take strong action now. [...] It would already be very difficult and costly to aim to stabilise at 450ppm CO_2e. If we delay, the opportunity to stabilise at 500-550ppm CO_2e may slip away.'"(Stern 2006). Likewise, the benefits of addressing CO_2 for ocean acidification also have the ancillary effect of slowing global warming and preventing costs associated with climate change.

The recently proposed rule to reducing power plant CO_2 emissions calculates both costs and benefits—notably the benefits far exceed the costs. The recently proposed rules for reducing power plant carbon emissions, calculates both costs and benefits for a more modest reduction. EPA projects that the annual compliance cost will be $4.3 to $5.5 billion (in 2011 dollars, depending on discount rate) in 2020 and $5.5 billion (for a 5% discount rate) in 2030.[66] The total combined climate benefits and health co-benefits are estimated to be $15.6 to $88 billion in 2020 and $32.3 to $151 billion in 2030 (depending on discount rate and the options chosen).[67] The insurance industry also is well aware of the potential costs of failing to address CO2 emissions and its associated effects, including: "[h]urricanes and other flooding events … [h]ealth issues associated with heat waves… more airborne allergens, rising temperatures, greater humidity, more wildfires, and more dust and particulate pollution may considerably exacerbate upper respiratory disease (rhinitis, conjunctivitis, sinusitis, asthma) and cardiovascular disease."[68] A European insurance company estimates losses from extreme climate change events of 37% within a decade, over $1 trillion under bad circumstances.[69] The increasing frequency and severity of storms in the U.S. has caused damages to increase 60-fold from 1950s to the 1990s.[70]

Petitioners ask that action to mitigate ocean acidification under TSCA be initiated, either through TSCA section 6 (e.g., requiring "repurchasing" relief using sequestration, emission reductions, etc.), or through section 4 in order to determine the need for action under section 6 and the most effective mitigation strategies. In any case, petitioners suggest that costs be apportioned among

[65] According to the Working Group itself, DICE "offers the best insight into the SCC if the world were to experience catastrophic climate change." *See* Working Group, *supra* note 62, at 16-A-35.
[66] EPA, Regulatory Impact Analysis Technical Document EPA-452/R-14-002 (June 2014).
[67] *Id.*
[68] National Association of Insurance Commissioners, The Potential Impact of Climate Change on Insurance Regulation at 10 (2008).
[69] See e.g. Allianz, Climate Change and the Financial Sector: An Action Plan; Evan Mills, Responding to Climate Change: The Insurance Industry Perspective.
[70] Mills, E. Insurance in a Climate of Change, Science 308: 1040 (2005).

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CO_2 emission contributors according to the cumulative CO_2 emission inventory information EPA has collected.[71]

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In summary, the weight of the scientific information on ocean acidification is sufficient to make a determination that CO_2 poses an unreasonable risk, to the extent that EPA declines to find the data adequate, then EPA must develop a test rule under TSCA section 4 as described below.

C. Alternatively, EPA Must Require Testing to Develop Adequate Data

EPA must make a determination as to whether adequate data exist to evaluate the environmental and health effects of CO_2. There is well-established scientific information on the risk of CO_2 on the environment, but if EPA determines that the data are insufficient then it must develop a testing rule.

In enacting TSCA, Congress declared that "adequate data should be developed with respect to the effect of chemical substances and mixtures on health and the environment and that the development of such data should be the responsibility of those who manufacture and those who process such chemical substances and mixtures."[72] Accordingly, section 4 directs EPA to require additional testing upon determining that "the manufacture, distribution in commerce, processing, use, or disposal of chemical substance or mixture … may present an unreasonable risk of injury to health or the environment," or if the chemical is produced in substantial quantities and there is a potential for a substantial quality to be released into the environment.[73]

1. CO_2 May Present an Unreasonable Risk

As described in depth in this petition, CO_2 may present an unreasonable risk to the environment. EPA interprets this to mean that there is a "substantial (i.e., more than theoretical) probability" of unreasonable risk to the environment or health.[74] The information in this petition meets the threshold for a testing rule and establishes a substantial probability that CO_2 poses an unreasonable risk to the environment, but EPA need not even make such a determination because CO_2 is produced in such large volumes that it clearly meets the criterion of exposure of substantial quantities being released into the environment.

2. Substantial Quantities of CO_2 Are Released into the Environment

It is undeniable that substantial qualities of CO_2 are released into the environment. EPA established a threshold value of one million pounds for a release of a chemical to be substantial. *TSCA Section 4(a)(1)(B) Final Statement of Policy; Criteria for Evaluating Substantial*

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[71] This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program.
[72] 15 U.S.C. § 2601(b)(1).
[73] 15 U.S.C. § 2603 (a)(1)(A), (B)(i).
[74] *Chemical Mfrs. Ass'n v. EPA*, 859 F.2d 977, 988 (D.C. Cir. 1988).

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Production, Substantial Release, and Substantial or Significant Human Exposure, 58 Fed. Reg. 28736, 28746 (May 14, 1993). According to the IPCC:

> From 1750 to 2011, CO_2 emissions from fossil fuel combustion and cement production have released 375 [345 to 405] GtC to the atmosphere, while deforestation and other land use change are estimated to have released 180 [100 to 260] GtC. This results in cumulative anthropogenic emissions of 555 [470 to 640] GtC.

(IPCC 2013, Summary for Policymakers).

In 2012, a total of 9.7 gigatonnes of CO_2 were released into the atmosphere from fossil fuel combustion and cement production (Global Carbon Project 2013). These emissions are expected to increase to 9.9 gigatonnes in 2013 (*Id.*). The United States contributed 14% of CO_2 emissions to the atmosphere (*Id.*). Models estimate that between 2003 and 2012, the oceans absorbed 27% of CO_2 from the atmosphere (*Id.*). Over the next millennium, the oceans will absorb 90% of anthropogenic CO_2 (Kleypas et al. 2006).

Therefore, the threshold of substantial release is exceeded by more than a million times over.

3. Recommendations for Testing

EPA should consider a test rule to fill the information gaps needed to make a determination of whether CO_2 presents an unreasonable risk of injury to the environment. Some recommendations for consideration include:

- Testing CO_2 reduction strategies. For example, research and development for emissions reduction strategies that include alternative practices, conservation, alternative fuels. Testing CO_2 sequestration and capture approaches, and assessing attainable CO_2 emissions reductions for industries with significant CO_2 emissions.
- Conducting a vulnerability assessment for marine and coastal species and ecosystems. Determining atmospheric CO_2 levels necessary to conserve marine ecosystems from dangerous ocean acidification. Emissions scenarios are important for informing policy approaches to acidification.
- Forecasting species' responses to ocean acidification using modeling tools to predict range shifts, demographic and population trends, and physiological responses across taxonomic groups using a range of climate models, emissions scenarios, and management timelines (25, 50, 100 years). Identify wildlife species and ecosystems imperiled by ocean acidification by evaluating range shift models and population viability models run under future ocean acidification levels. Recommend conservation actions, including protected status, for species that are most at risk. Protect species across their range since populations are likely to have different adaptations to local oceanic conditions.
- Determining the economic values of ecosystems that are at risk from ocean acidification and the costs of reducing CO_2 emissions to preserve those ecosystems.

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Additionally, EPA can use guidance on research needs based on existing research plans. There are a number of sources recommending research and data needs (National Research Council 2013; Washington State Blue Ribbon Panel 2012; National Research Council 2010).

According to TSCA, developing the data is "the responsibility of those who manufacture and those who process such chemical substances and mixtures."[75] For example, responsibility could be apportioned based on the historical carbon emissions from the EPA Greenhouse Gas Emission Inventory together with current emissions. Typically for test rules with multiple responsible parties consortiums are set up to comply.[76] Here, for example, utilities, cement and lime manufacturers, waste incinerators, and other large producers of CO_2 should be responsible for developing unbiased, independent data.

While this may seem like a complicated undertaking, EPA has successfully completed more complex test rules. For example, from 1998 through the present, the agency used three sets of regulatory test rules under TSCA to collect chemical data for almost 3,000 high production volume (HPV) chemicals, including over 10,000 individual studies with data from domestic and foreign producers.[77]

EPA must develop test rules under TSCA section 4 for research and data development focused on information essential for making a definitive TSCA section 6 finding. These would include risk, benefit and cost information.

D. Inadequacy of Existing CO_2 Reduction Strategies

Petitioners are aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. However, these actions by themselves, while laudable, will not stabilize atmospheric CO_2 at a level which will prevent widespread harm from ocean acidification.

1. Global Greenhouse Gas Emissions Are Increasing Substantially

The atmospheric concentration of CO_2 reached 400 parts per million (ppm) for the first time in human history in May, 2013, compared to the pre-industrial concentration of ~280 ppm (Scripps Institution of Oceanography 2013). The current CO_2 concentration has not been exceeded during the past 800,000 years and likely not during the past 15 to 20 million years (Denman et al. 2007; Tripati et al. 2009). Atmospheric CO_2 emissions have risen particularly rapidly since the 2000s (Raupach et al. 2007; Friedlingstein et al. 2010). The global fossil fuel CO_2 emissions growth rate was 1.0% per year in the 1990s compared with 3.1% per year since 2000, and this growth rate has largely tracked or exceeded the most fossil-fuel-intensive emissions scenarios projected by the IPCC (A1FI and RCP 8.5) since 2000 (Raupach et al. 2007, Peters et al. 2012). The CO_2 emissions growth rate fell slightly in 2009 due largely to the global financial and economic

[75] 15 U.S.C. § 2601
[76] 15 U.S.C. § 2602 (b)(3)(A)
[77] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm (last accessed June 28, 2015).

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crisis; however, the decrease was less than half of what was expected and was short-lived (Fiedlingstein et al. 2010). In 2014 and 2015, global CO_2 concentrations exceeded 400ppm.[78]

2. U.S. Measures to Reduce Greenhouse Gas Emissions Are Insufficient

EPA has taken some initial steps toward curbing greenhouse pollution under the Act. In 2009, the agency issued a formal finding that greenhouse pollution endangers public health and welfare and moved to limit emissions from passenger cars and trucks. The EPA also acknowledged that major new or modified "stationary" sources of greenhouse pollution, like power plants and factories, must obtain permits and control their emissions before beginning construction. However, it narrowed the scope of this requirement considerably under its so-called "tailoring rule," which initially limits the permitting program to only a few hundred very large sources of greenhouse gases, letting a huge number of smaller — but still significant — sources off the hook.

While existing domestic laws including the Clean Air Act, Energy Policy and Conservation Act, Clean Water Act, Endangered Species Act and others provide authority to executive branch agencies to require greenhouse gas emissions reductions from virtually all major sources in the United States, these agencies are either failing to implement or only partially implementing these laws for greenhouse gases. The landmark 2014 pact with China to reduce greenhouse gas emissions is significant, but there is little to ensure it is enforced and implemented. According to the plan, United States will reduce CO_2 emissions 26 to 28% below 2005 levels by 2025.

Proposed power plant rules also fail to do enough to cut CO_2 pollution. Using the Clean Air Act, the president aims to reduce existing power plant emissions 30 percent below 2005 levels (or about 7.7 percent below 1990 levels, the base year for the international climate treaty) by 2030. But international scientists warned years ago that developed countries like the United States must reduce their emissions 25 percent to 40 percent below 1990 levels by 2020 to avoid tipping the scales further toward a climate catastrophe. Likewise, the recently announced plans to limit power plant emissions (Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units) focuses on emission reduction. Power plants are responsible for about a third of our carbon emissions, and the rule is designed to reduce those emissions by almost a third by 2030. This would result in a 10% decrease in 15 years. Stabilizing atmospheric concentration to prevent further acidification of the oceans would require about an 80% decrease in all emissions. Clearly this is a good first step, but by itself inadequate to address acidification.

EPA has issued a rulemaking regulating greenhouse gas emissions from automobiles that will reduce greenhouse emissions emitted per vehicle mile traveled by passenger vehicles in the future. But because the improvements are modest and more vehicles are projected to drive more miles in the future, the rule will not reduce emissions from this sector overall but will only slow the rate of increase.[79] Meanwhile, even the government concedes that "these reductions in emissions are not sufficient by themselves to reduce total HD vehicle emissions below their 2005

[78] NOAA, Trends in Atmospheric Carbon Dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/
[79] EPA, Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule, 75 Fed. Reg. 25324 (May 7, 2010).

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levels by 2020."[80] This means that the vehicle rule is far from achieving emissions goals agreed to by the U.S. in the Copenhagen Accord, which aim to keep global warming below 2˚C.

The EPA has also to date issued only a single proposed rule under the new source pollution standard program for stationary sources of pollution, for electric generating units (power plants). While there is enormous potential to reduce emissions through this program overall and through the power plants rule in particular, the EPA has instead proposed a weak and flawed rule that it admits will not reduce emissions from these sources between now and 2020 compared to what would be expected without the rule.[81] Indeed, in the rulemaking the EPA conceded that new power plant rule on greenhouse gas emissions "will not have direct impact on U.S. emissions of greenhouse gases under expected economic conditions."[82]

While full implementation of our flagship environmental laws, particularly the Clean Air Act, would provide an effective and comprehensive greenhouse gas reduction strategy, due to their non-implementation, existing domestic regulatory mechanisms must be considered inadequate to protect marine species from climate change and ocean acidification.

3. International Measures to Reduce Greenhouse Gas Emissions Are Inadequate

International initiatives are also currently inadequate to effectively address climate change. The United Nations Framework Convention on Climate Change, negotiated in 1992 at Rio de Janeiro, Brazil, provides the forum for the international negotiations. In the Framework Convention, signed and ratified by the United States, the world agreed to take the actions necessary to avoid dangerous climate change. Parties to the Convention also agreed as a matter of fairness that the world's rich, developed countries, having caused the vast majority of emissions responsible for the problem, would take the lead in solving it. It was not until the 1997 meeting in Kyoto, Japan, that the first concrete, legally binding agreement for reducing emissions was signed: the Kyoto Protocol. The Protocol requires the world's richest countries to reduce emissions an average of 5 percent below 1990 levels by 2012, while developing nations also take steps to reduce emissions without being subject to binding emissions targets as they continue to raise their standard of living. The United States has been a major barrier to progress in the international negotiations. After the Clinton administration extracted many concessions from the rest of the world in exchange for the United States signing on in Kyoto, the Senate rejected the equity principles behind the Convention, saying the United States should not agree to reduce its own emissions unless all other countries — regardless of their responsibility or ability — were similarly bound. Citing the same excuses, President George W. Bush repudiated the Kyoto Protocol entirely. Thus the United States is the only industrialized country in the world that has yet to ratify the Kyoto Protocol. The United States negotiating team under both the George W. Bush and the Obama administrations has pursued two primary objectives in the international talks: to refuse any legally binding emissions reduction commitments until all other

[80] NHTSA, Medium- and Heavy-Duty Fuel Efficiency Improvement Program – Final Environmental Impact Statement (June 2011).
[81] EPA, Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units, 77 Fed. Reg. 22392, 22430-33 (April 13, 2012).
[82] *Id.* at 22401.

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countries— but particularly China and India — do so, and to push back the date for a new agreement. Not surprisingly, the United States had failed to meet its (never ratified) Kyoto pledge to reduce emissions to 7.2% below 1990 levels by 2012; to the contrary, U.S. emissions have increased by 10.5% since 1990 (EPA 2012).

Moreover, the Kyoto Protocol's first commitment period only sets targets for action through 2012, and there is still no binding international agreement governing greenhouse gas emissions in the years beyond 2012. While the 2009 U.N. Climate Change Conference in Copenhagen called on countries to hold the increase in global temperature below 2□C (an inadequate target for avoiding dangerous climate change), the non-binding "Copenhagen Accord" that emerged from the conference, and the subsequent "Cancún Accords" of 2010 and "Durban Platform" of 2011 failed to enact binding regulations that limit emissions to reach this goal.[83] Even if countries were to meet their Copenhagen and Cancún pledges, analyses have found that collective national pledges to cut greenhouse gas emissions are inadequate to achieve the 2°C target, and instead suggest emission scenarios leading to 2.5□C to 5□C warming (Rogelj et al. 2010; UNEP 2011; UNEP 2010). As of July 2013, many governments were not implementing the policies needed to meet their inadequate 2020 emission reduction pledges, making it more difficult to keep global temperature rise to 2□C and likely leading to a temperature rise of at least 3.5□C (USGCRP 2013). As noted in the NMFS Management Report, the U.S. has yet to issue regulations to limit greenhouse gas emissions in accordance with its pledge under the Copenhagen Accord (NMFS 2012).

CONCLUSION

In conclusion, this petition requires EPA to make a determination whether CO_2 poses an unreasonable risk to the environment therefore requiring regulation under section 6 of TSCA. In an extensive review of the literature on the impact of ocean acidification on marine fauna and ecosystem processes, the authors found that while additional research is called for, sufficient information exists to state with certainty that deleterious impacts on some marine species are unavoidable, and that substantial alteration of marine ecosystems is likely over the next century. (Fabry et al. 2008). If, nonetheless, EPA determines that the information is insufficient to make such a finding it must develop testing rules pursuant to TSCA section 4.

[83] The non-legally binding Copenhagen Accord of 2009 and Cancún Accords of 2010 recognize the objective of limiting warming to 2°C above pre-industrial temperatures, but do not enact binding regulations to achieve this goal (http://cancun.unfccc.int/cancun-agreements/main-objectives-of-the-agreements/#c33; unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). According to the Durban Platform, developed and developing nations agreed to a process to develop a "new protocol, another legal instrument, or agreed outcome with legal force that will be applicable to all Parties to the UN climate convention"; this legal instrument must be developed as of 2015 and will not take effect until 2020 (unfccc.int/resource/docs/2011/cop17/eng/l10.pdf).

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August 23, 2013

National Freedom of Information Officer
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, NW (2822T)
Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1) All records discussing, describing, referring to or interpreting the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*").

2) To the extent not provided in response to request #1, all records of information relied upon by the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*") in the development of the *2010 TSD on SCC* and the *2013 TSD on SCC*, including but not limited to:

   a) Any presentations, reports, studies, computer or other analytical models, and data (including modeling data) created by or on behalf of the *IWG on SCC*, or provided to or obtained by the *IWG on SCC*.

   b) Any records that discuss, describe, interpret or otherwise relate to the Integrated Assessment Models ("IAMs") referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to:

      i) any inputs and assumptions (including but not limited to assumptions on discounting, equilibrium climate sensitivity, and socioeconomic variables);

      ii) the results of any modeling runs or scenarios generated by the IAMs (in both paper copies and in original electronic form); and

      iii) the source codes for the DICE, PAGE and FUND models referred to in the *2010 TSD on SCC* or *2013 TSD on SCC* (in the original electronic form, such as native modeling formats).

Sidley Austin (TX) LLP is a Delaware limited liability partnership doing business as Sidley Austin LLP and practicing in affiliation with other Sidley Austin partnerships.

c) Any records that identify, discuss, interpret or relate to any uncertainties or error rates of the *2010 TSD on SCC* or the *2013 TSD on SCC* or any of the IAMs referenced in or relied upon by the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to any limitations in using the DICE, PAGE or FUND models to make predictions beyond the year 2100.

d) Any records that discuss, interpret or explain why the social cost of carbon estimated by the *2013 TSD on SCC* is approximately 60% higher than that estimated by the *2010 TSD on SCC*.

e) Any records that discuss, interpret, relate to, explain or make recommendations or decisions regarding global versus domestic measures of the social cost of carbon with respect to the work of the *IWG on SCC* and the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the calculation or use of a domestic SCC for the United States.

3) Any records discussing, interpreting, transmitting or relating to any critiques, analyses or studies of the *2010 TSD on SCC* or *2013 TSD on SCC*, or any data, information or models relied on or referred to in the *2010 TSD on SCC* or *2013 TSD on SCC*, including but not limited to the work or statements of Robert Pindyck.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

For all records responsive to these requests that are not produced based on an asserted exemption from disclosure, please prepare a privilege and/or exemption log describing, at a minimum: (i) the type of record withheld; (ii) the date(s) of the creation of the record; (iii) the subject of the record; (iv) the identity of the author and all recipients of the records; and (v) a detailed description of the basis upon which EPA is withholding the record (e.g., the claim of privilege, FOIA exemption, etc.). To the extent any responsive documents are withheld based upon a claim of privilege or other exemption from disclosure, please produce redacted copies of all non-privileged or non-exempt factual material contained within such documents.

As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the

deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

I confirm in advance my willingness to pay for all reasonable costs associated with searching for and copying these records. However, should these costs exceed $500, I ask that you contact me prior to proceeding.

Thank you for your prompt attention to this request. Please direct any inquiries, notices, or determinations to me at (713) 495-4508 or cbell@sidley.com.

Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

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National Freedom of Information Officer
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Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records identifying the dates and attendees of meetings, or dates of and participants in teleconferences or webinars involving, the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*"), or any committee, working group, sub-committee, task force or project group thereof.
2. Any government contracts used to hire anyone to assist in the preparation of the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*"), including but not limited to, any government contracts used to hire anyone to perform the Integrated Assessment Modeling referenced in the *2010 TSD on SCC* or the *2013 TSD on SCC*.
3. Any records that describe, identify, contain, interpret or provide the dates or substance of briefings of political appointees in the Executive Branch on the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to, PowerPoint presentations. In the response, please produce the requested briefing records in their native original electronic form (PowerPoint, Word, etc.).
4. All electronic mail, WebEx documents, Google Docs, text messages, instant messages, voice mails, facsimiles or any other records relating to the *2010 TSD on SCC* or *2013 TSD on SCC* that were sent to any person outside the *IWG on SCC*, including but not limited to documents sent to or received from: any of the authors of the publications listed in the References section of the *2010 TSD on SCC* or *2013 TSD on SCC*; any other academics; government contractors; consultants; Sierra Club, Natural Resources Defense Council or other

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nongovernmental groups; and any other third-party whatsoever that was not part of the *IWG on SCC*.

5. All records discussing, describing, interpreting or relating to the applicability of or compliance with the Information Quality Act (P.L. 106-554, Section 515, 144 Stat. 2763 (2001)), or any Information Quality Act Guidelines published by the Office of Management and Budget, with respect to the work of the *IWG on SCC* or development, publication, use or dissemination of the *2010 TSD on SCC* or the *2013 TSD on SCC*.

6. All records discussing, interpreting or relating to the applicability of the Administrative Procedure Act (5 U.S.C. § 500 et seq.) to the *2010 TSD on SCC* or the *2013 TSD on SCC*, including but not limited to whether those documents should have been published for public review and comment.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and all other types of records in the possession, control or custody of EPA or contractors working for EPA.

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As required by law, please provide the above records within twenty (20) business days of receipt of this FOIA Request. 5 U.S.C. § 552(a)(6)(A)(i). If it appears that it may not be possible to provide all of the records by the statutorily-mandated deadline, please provide the responsive records that are available as of the deadline (i.e., do not withhold responsive records past the deadline while searching for additional records), and please contact me promptly regarding any scheduling issues.

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Sincerely,

/s/ Christopher L. Bell

Christopher L. Bell

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National Freedom of Information Officer
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Washington, DC 20460

Dear Sir or Madam:

This is a request made pursuant to the Freedom of Information Act ("FOIA"), 5 U.S.C. § 522 and the implementing regulations of the Environmental Protection Agency ("EPA"), for copies of the following records:

1. All records discussing, describing, referring or providing direction to, communicating to or about, or interpreting the formation, organization, structure, authority, activities, meetings, recommendations or decisions of the *Interagency Working Group on Social Cost of Carbon, United States Government* ("*IWG on SCC*").
2. All records describing or discussing any past, on-going (as of the date of this submission) or planned work of the *IWG on SCC*.
3. All records describing, discussing or interpreting how the *Technical Support Document: -- Social Cost of Carbon for Regulatory Impact Analysis -- Under Executive Order 12866* (February 2010) ("*2010 TSD on SCC*") or the *Technical Support Document: -- Technical Update to the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013) ("*2013 TSD on SCC*") have been or are to be used by Federal agencies, including but not limited to the use of these documents in the development and promulgation of regulations and in making policy decisions.
4. All records discussing or interpreting how the *2010 TSD on SCC* or the *2013 TSD on SCC* have been used or relied on, or are planned to be used, by EPA in any regulation proposed or promulgated by EPA, or in any policy decisions made by or guidance documents created by EPA.

For purposes of this request, "records" mean documents, information, memoranda, letters, reports, drafts, communications, records of communications, telephone message records, calendars, agendas, meeting sign-in sheets, presentations, handwritten or typed notes, facsimile transmissions, electronic mail, transcripts or recordings (audio or visual) of meetings, tapes and

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Pursuant to the Freedom of Information Act ("FOIA") 5 U.S.C. § 552, and the implementing regulations of the U.S. Environmental Protection Agency ("EPA"), 40 C.F.R. Part 2, I am requesting a copy of the following EPA records:

1. All petitions for rulemaking of any kind submitted to the EPA Administrator related to any statute or regulation under which the EPA Administrator has the authority to promulgate regulations from January 1, 2013, to the present. These include, but are not limited to, petitions under the Clean Air Act, the Clean Water Act, the Resource Conservation and Recovery Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Toxic Substances Control Act, and the Federal Insecticide, Fungicide, and Rodenticide Act.

2. All notices of intent to sue EPA or its Administrator, dated from January 1, 2013, to the present, under any of the statutes listed above or under the Administrative Procedure Act for:

a. Failure to timely act on any petition for rulemaking;

b. Failure to meet any statutory, regulatory, or other deadline; or

c. Failure to meet any nondiscretionary obligation..

This request is only seeking for the specific items referred to above, all of which would have been submitted to EPA by third parties. Therefore, this request does not seek any records that are exempt from disclosure.

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Please direct any inquiries, notices, or determinations to me at (202) 736-8281. Thank you for your anticipated assistance.

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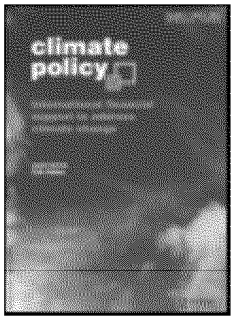

Climate Policy

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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National Center for Environmental Economics, US Environmental Protection Agency, 1200 Pennsylvania Avenue, Washington, DC 20460, USA

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

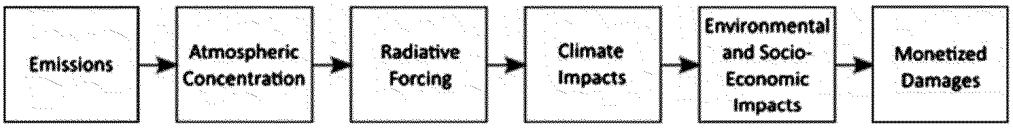

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4}\ - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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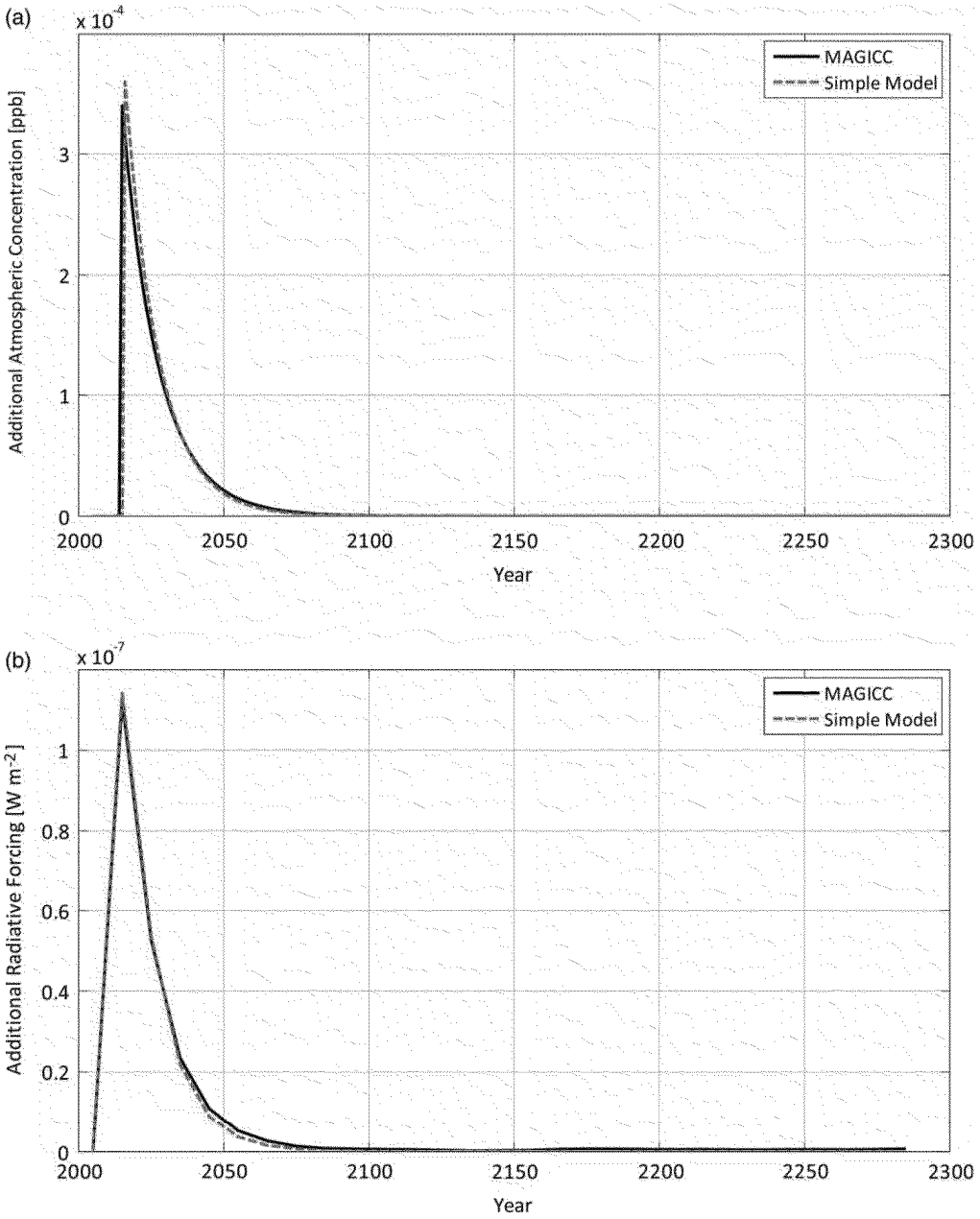

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})], \right. \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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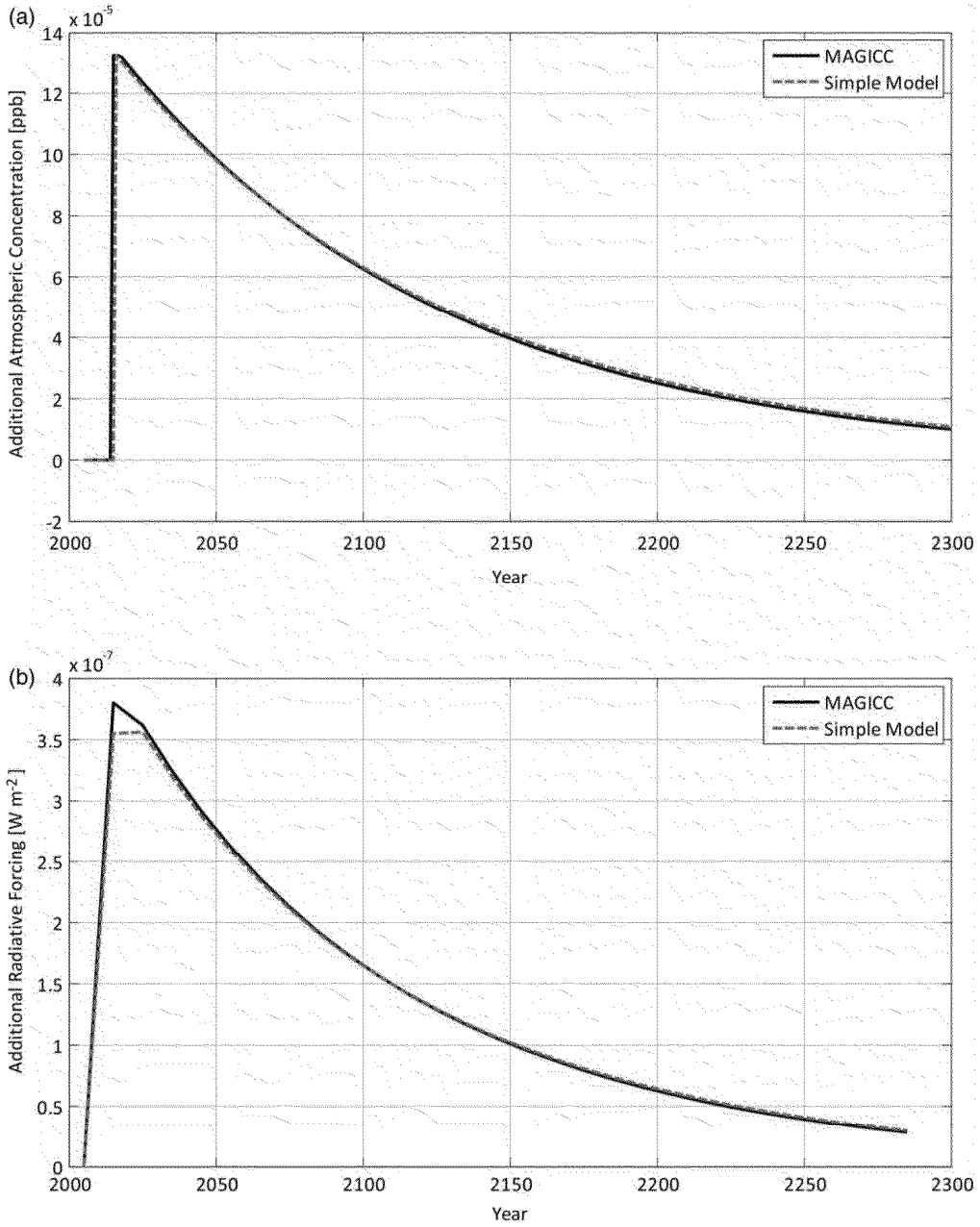

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

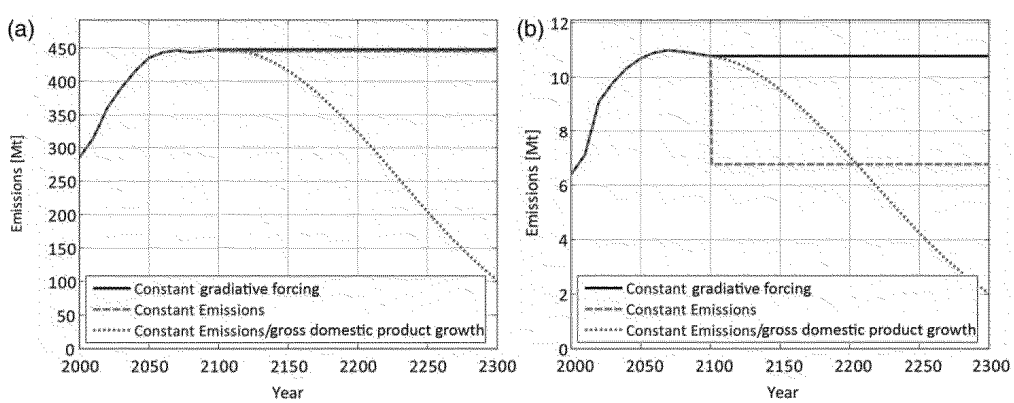

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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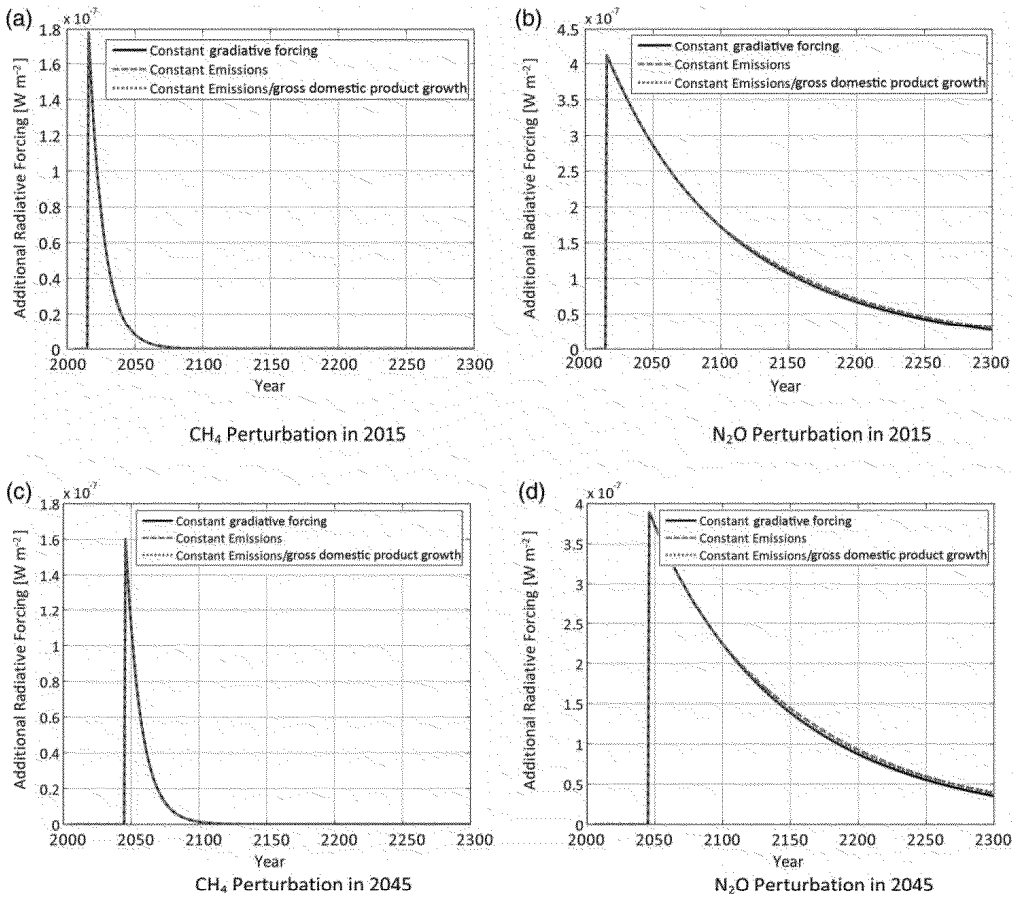

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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Viewpoint

Firm performance and employment in the EU emissions trading scheme: An empirical assessment for Germany

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Abstract

This paper empirically investigates the role of the EU Emissions Trading Scheme (EU ETS) for firm performance and employment in Germany. We provide an overview of relative allowance allocation within the EU ETS as well as an econometric analysis for a large sample of German firms covered by the scheme in order to assess the impacts of EU emissions regulation on both firm revenues and employment. The dataset indicates that the EU ETS was in an overall long position in 2005, although allowance allocation was very heterogeneous across member states. Our econometric analysis suggests that, within the first phase of the EU ETS, relative allowance allocation did not have a significant impact on firm performance and employment of regulated German firms.
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Keywords: EU ETS; Competitiveness; Employment

1. Introduction

In 2005, the European Union Greenhouse Gas Emissions Trading Scheme (EU ETS) was launched (European Union, 2003). The scheme represents a cornerstone of the efforts by EU member states to fulfil the emissions reduction targets under the Kyoto Protocol. This agreement requires European countries to reduce their greenhouse gas emissions on average by 8% until 2012 compared with 1990 emissions levels (UNFCCC, 1997). The EU ETS covers European producers in four sectors, namely energy (e.g. electric power, oil refinement), production and processing of ferrous metals, minerals (e.g. cement, glass), as well as pulp and paper. The ETS currently covers almost half (46%) of the total CO_2 emissions of EU countries. While in the scheme's first phase (2005–2007) almost all emission allowances are grandfathered by means of National Allocation Plans (NAPs) of each member state and only up to 5% may be auctioned, in the second phase (2008–2012) the auctioning limit rises to 10%. Furthermore, the amending directive linking the EU ETS with the Kyoto Protocol's project-based mechanisms enables EU companies to generate emissions reductions by means of the Clean Development Mechanism (CDM) or Joint Implementation (JI) (European Union, 2004).

Since its initiation, the EU ETS has been accompanied by discussions on potential losses in competitiveness in international markets of companies that are covered by the EU ETS legislation.[2] Against this background, this paper presents a first empirical assessment of the effects of the EU ETS on firm performance, i.e. competitiveness, and employment. Following Balassa (1962), we define competitiveness as a firm's ability ''to sell on foreign and domestic markets'' and approximate this ability by firms' market revenues. We rely both on real-world data on allocated allowances and verified emissions for the first trading period from the EU Community Independent Transaction Log (European Union, 2007) and on economic firm-level data from two comprehensive databases.

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[2]For a recent overview on model-based assessments of costs and competitiveness effects of the EU ETS, see Oberndorfer and Rennings (2007).

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Previous quantitative studies have assessed the efficiency aspects and competitiveness implications of the EU ETS predominantly in numerical modeling frameworks. Böhringer et al. (2005) show that the exclusive coverage of energy-intensive installations by EU ETS implies that—in the absence of the potential use of CDM and JI—the remaining industries have to be regulated by complementary abatement policies in order to meet the national Kyoto targets. Such a hybrid emission regulation can cause large inefficiencies within EU economies, but may also worsen the prospects of linking the EU ETS to emerging emissions trading schemes beyond Europe (see Anger, 2007). Unlike employment aspects of the EU ETS, competitiveness implications of the current European trading scheme have been analyzed in numerical model frameworks (Kemfert et al., 2005; Klepper and Peterson, 2004; Peterson, 2006). The sectoral competitiveness implications of allowance allocation under the EU ETS have been assessed both for the European electricity industry (Neuhoff et al., 2006) and for the cement sector (Demailly and Quirion, 2006). Enlarging the purely European perspective, Alexeeva-Talebi and Anger (2007) assess both the economy-wide and the sectoral competitiveness effects of linking the EU ETS internationally to emerging trading systems outside Europe (such as Japan, Canada or Australia) within an applied general equilibrium model framework.

The previous empirical literature on emissions regulation under the EU ETS is rather scant. Analyzing the verified emissions of the participating installations as well as the respective allowances allocated, Ellerman and Buchner (2006) conclude that ''over-allocation occurred and that its magnitude may have been as much as 100 million EU allowances''. Kettner et al. (2007) present similar findings, suggesting that in the first EU ETS trading year the scheme was in a long position regarding emissions allowances. Moreover, to date there is no empirical contribution available assessing the competitiveness or employment impacts of emissions allocation under the EU ETS. Our paper aims at starting to fill this gap. In this respect, the contribution of this analysis is twofold: Relying on installation-level allocation data from the EU Community Transaction Log in 2005, we (i) descriptively assess the relative allowance allocation under the EU ETS at the national level and (ii) econometrically test for competitiveness and employment impacts of the EU ETS for a large sample of German companies.

The present article is structured as follows. Section 2 summarizes the empirical literature. Section 3 discusses the relative allowance allocation in Europe as well as the data underlying the empirical analysis for Germany. Section 4 presents the econometric assessment and Section 5 concludes.

2. Literature review

The necessity of environmental regulation is mainly based on the reasoning that there are social costs of negative externalities such as pollution. However, strict environmental regulation is often accused of harming the competitiveness of the affected sector or firm. Such adverse economic effects (and especially effects on competitiveness) of environmental regulation are challenged by the so-called Porter hypothesis, suggesting that environmental regulation provides incentives for companies to innovate and that these innovations can stimulate economic growth and competitiveness of the regulated country (Porter and van der Linde, 1995).

In the context of competitiveness and employment, an important characteristic of emissions trading schemes is the choice of the underlying allocation method. There are several studies dealing with this issue: Demailly and Quirion (2007) quantify the impact of the EU ETS on production and profitability as two dimensions of competitiveness for the iron and steel industry. They find that competitiveness losses for this sector are small but are significantly determined by pass-through rates and the updating of allocation rules. While emissions-based updating should be avoided as it creates perverse investment incentives, output-based updating has ambiguous competitiveness effects—softening production losses, but reducing the likely gains in earnings before interests, taxes, debt and amortization. Böhringer and Lange (2005) investigate the trade-off between compensation and economic efficiency for output- and emissions-based allocation rules in an international emissions trading scheme. They find that the output-based rule not only induces substantially lower efficiency losses than the emissions-based rule, but also performs better in ameliorating adverse production and employment effects for energy-intensive industries. Fischer and Fox (2007) present a welfare analysis of alternative emissions allocation rules within a domestic US emissions trading scheme, focusing on sectoral and international leakage as generated by restricted sectoral coverage of domestic ETS and unilateral action. They find that, given domestic and international leakage, output-based allocation of emissions permits to the covered sectors is preferable to auctioned permits in welfare terms, even when allowing for pre-existing tax distortions. Moreover, grandfathered permits generate the highest welfare costs of emissions regulation.

Our empirical literature review focuses on competitiveness, as the empirical literature on employment effects of environmental regulation is rather scant. One exception is Golombek and Raknerud (1997), who empirically assess the employment effects of imposing environmental standards on polluting firms. Using Norwegian data they find that, for two out of three manufacturing sectors, firms under strict environmental regulations had a higher tendency to increase employment and a lower tendency to exit than firms under weak or no environmental regulation.

Empirical analysis of the effects of environmental regulation on competitiveness or, more general, economic performance of firms or sectors is rather rare, too, as truly

exogenous measures are often barely accessible. Pickman (1998), Brunnermeier and Cohen (2003) as well as Jaffe and Palmer (1997) use US Pollution and Abatement Costs and Expenditures (PACE) as a proxy of the stringency of environmental regulation in order to test for the innovation effects of US industries. However, such costs may depend on other factors such as the response to regulation, as well as the right measurement and exact self-report of firms and industries. Therefore, it is unclear whether compliance costs under- or overstate true regulation costs (Brunnermeier and Cohen, 2003). Pickman (1998) as well as Brunnermeier and Cohen (2003) find evidence that those costs positively affect innovation, while the results of Jaffe and Palmer (1997) do not confirm such causal relationship. What is more, it is controversial if a positive effect of environmental regulation on innovation (or even environmental innovation) would imply a positive competitiveness record of environmental regulation, as e.g. opportunity costs (e.g. other investment or conventional innovations that have not been realized due to the burden of regulation costs) are neglected in such a setting.

Such problems do not arise in event studies on environmental regulation. Such studies measure the impact of environmental regulation on stock returns of firms (possibly) affected. They often only compute short-term financial market reactions, however. Furthermore, they hinge on the assumptions of efficient financial markets and of no anticipation of regulation by the market actors, which may often be very crucial for the interpretation of the results computed. Butler and McNertney (1991) consider the effect of elections, namely the 1982 state-wide gubernatorial elections in six US states. These states were identified as those where the election results were uncertain and expected to affect environmental regulation for energy utilities. The study shows that in those states in which the victory of a democratic governor was most unpredictable significantly negative cumulative abnormal returns arise. Blacconiere and Northcut (1997) consider the impact of the US Superfund Amendments and Reauthorization Act (SARA) of 1986 on stock returns for corporations from the chemical industry, finding significant negative cumulative abnormal returns only for 17 out of 26 SARA-related events analyzed. Two more recent studies consider the effect of the US Clean Air Act Amendments of 1990 on stock returns for energy utilities (Diltz, 2002; Kahn and Knittel, 2003). Both studies cannot show sharp financial market reactions. Oberndorfer and Ziegler (2006) find that the German phasing out of nuclear energy (similarly to Butler and McNertney (1991), measured by the victory of the acting government with participation of the Green party in the 2002 German Federal Elections) had at least no general negative short- and mid-horizon effect on the economic performance of energy corporations. As far as the EU ETS is concerned, there are not yet empirical contributions available that measure competitiveness impacts of the introduction of and allocation inside of the scheme.

All in all, most of the existing studies find only weak evidence of an effect of environmental regulation on firm performance. Furthermore, all groups of approaches tackling the question about performance—competitiveness—impacts of environmental regulation have their idiosyncratic flaws: While innovations do not represent an ideal competitiveness indicator and the use of compliance costs as a proxy for regulation is not uncontroversial, most event studies only focus on short-term financial market reactions given environmental regulation. For the EU ETS, no empirical contribution on competitiveness impacts is available yet. Preliminary and descriptive evidence, however, suggests that the scheme is characterized by a relatively generous emissions cap compared with verified emissions.

3. Data and variables

In this section, we present the data basis underlying the emissions allocation within the EU ETS. This is done by firstly giving an overview over (relative) allocation at the national level for all EU ETS countries. In a second step, we present the data basis used for our empirical policy assessment of employment and competitiveness effects associated with EU ETS relative allowance allocation in Germany.

3.1. EU ETS data

The 2005 allocation data were extracted from the EU Community Transaction Log (European Union, 2007). The allocation factor measures the allocation of EU emissions allowances relative to the actual emissions of the respective entity and is calculated as the quotient of allowances allocated to the verified emissions. The allocation factor thus shows the relationship between the amount of allocated allowances and actual emissions, i.e. an allocation factor larger than 1 suggests that an entity has received allowances that exceed its emissions, while an allocation factor smaller than 1 suggests that the respective entity either has to buy additional emissions allowances or abate some of its emissions in order to comply with EU ETS regulation. In this context, one problem may be that verified emissions do not stem from a pre-EU ETS period (this emissions data is actually not available) but from 2005, and are thus of ex-post nature. Therefore, relative allocation cannot be distinguished from actual early abatement in 2005 and also the allocation factor has an ex-post character.[3] First evidence, however, suggests that abatement in 2005 remained relatively low, so that the allocation factor should be at least a very good indicator for relative allocation (Ellerman and Buchner, 2006).

[3] Moreover, note that the allocation factor is dependent on factors such as stochastic variations in weather, production, energy prices, or other variables affecting emissions.

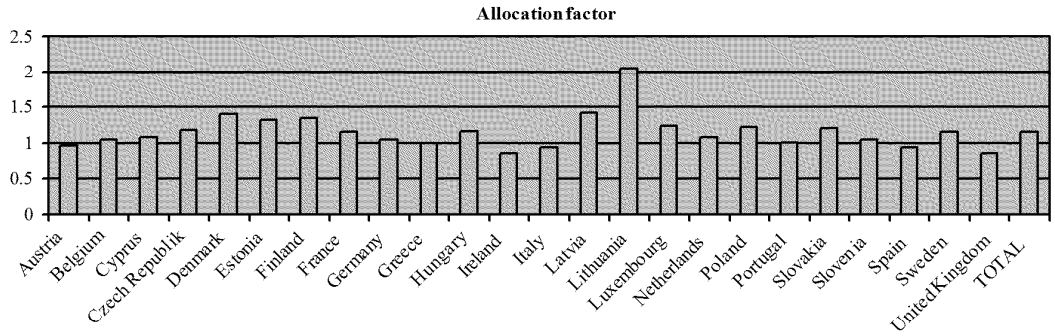

Fig. 1. Allocation factors at an aggregate national level for EU ETS countries (source: European Union, 2007; own calculations).

Fig. 1 shows the allocation factor, aggregated at the national level and based on disaggregated installation level data from the EU Community Transaction Log, for all EU ETS countries. Our aggregated data rely on 10,276 installations, covering the entire set of identifiable EU ETS installations. It indicates that companies in some countries—e.g. Ireland and the UK—have received fewer allowances than their respective emissions, while companies from other countries have received a large relative amount of emissions allowances given their actual emissions. Noteworthy in this respect is Lithuania, with its companies having received allowances for more than twice of their actual emissions. For the EU ETS level, the data extracted from the EU Community Transaction Log suggest that, in 2005, the scheme as a whole was in a long position. Furthermore, it already indicates that the relative allowance allocation enormously differs across single entities. This is in line with the findings of Kettner et al. (2007).

More specifically, Kettner et al. (2007), consistently with our calculations, identified Lithuania as the country exhibiting the biggest ''net long'' position and Ireland and the UK as countries exhibiting the biggest ''net short'' position within the scheme. Additionally to our calculations, however, they provide information on long and short positions at the sector level, which is not in the focus of our analysis.

3.2. German sample

In the framework of an empirical analysis for Germany, we want to assess the impact of relative allocation of EU emissions allowances on competitiveness and employment at the firm level. The econometric analysis can only be conducted within a case study for Germany, as economic variables that could indicate the development of competitiveness and employment at the firm level up to 2005 were not available to us for all EU countries. Still, the econometric analysis may offer important insights into the economic effects of the EU ETS in Europe as a whole, as Germany is the most important country within the EU ETS, its companies representing about 24% of all allowances allocated. To our knowledge, our approach represents the first ex-post analysis of the economic impacts of the EU ETS.

For the purpose of this empirical investigation, EU ETS allocation data stemming from the Community Transaction Log (European Union, 2007) (i.e. the allocation factor, see above) were aggregated at the firm level for Germany. The relative emissions allocation data were subsequently matched with economic data from the CREDITREFORM database. Sectoral (indicator) variables were generated according to the four-digit NACE industry codes that are contained in the AMADEUS database. Our sector classification includes the business, electricity, energy, mining, coke & petroleum, pulp & paper, and (other) manufacturing sectors. For more detailed information on the economic, sectoral and emissions data employed in this analysis, please refer to Appendix A.

All in all, given our economic data, 419 German firms covered by the EU ETS could be analyzed in the empirical framework. Table 1 gives first information on the 2005 data from the Community Transaction Log and the CREDITREFORM database. It shows that, on average, the companies included in the empirical analysis have been, in comparison with all German EU ETS participating firms, relatively highly allocated with EU emissions allowances. While for Germany as a whole the allocation factor is 1.04, for the sample analyzed it is 1.24. Furthermore, the economic data indicate that, in 2005, the decisive year of our analysis, the firms included have, on average, under circumstances of shrinking revenues, reduced their number of employees. More than a quarter of our sample firms stem from the manufacturing sector; mining and coke & petroleum firms, in contrast, are very infrequent here. In all, 153 firms could not be classified in our sectoral classification (for an overview over the sectoral distributions, see Table A1).

4. Econometric analysis for Germany

4.1. Estimation approach

An econometric analysis is the only means to empirically measure the impact of relative allocation of EU emissions allowances on competitiveness and employment. In the

Table 1
Descriptive statistics of German firm data

Variable	No. obs.	Mean	Std. dev.	Min	Max
Allocation factor	419	1.24	0.57	0.26	5.95
Allowances allocated	419	603,961.5	4,795,754	272	9.02e + 07
Verified emissions	419	579,399	4,862,883	50	9.12e + 07
Revenues 2005ffi2004	419	ffi139.43	3982.08	ffi79,678.02	8361.04
Revenues 2004ffi2003	419	77.01	507.40	ffi320.02	8539.71
Revenues 2003ffi2002	419	ffi18.92	1917.70	ffi21,191.99	18,451.61
Revenues 2005	419	972.32	4423.90	0.16	56,172.84
Revenues 2004	419	1111.75	7340.71	0.16	135,850.90
Revenues 2003	419	1034.74	7080.48	0.16	131,569.00
No. employees 2005ffi2004	419	ffi413.08	5367.39	ffi73,336	22,660
No. employees 2004ffi2003	419	424.90	5328.04	ffi3508	72,712
No. employees 2003ffi2002	419	ffi80.21	705.73	ffi6899	3850
No. employees 2005	419	2705.22	20,010.84	1	384,723
No. employees 2004	419	3118.29	20,606.48	1	362,063
No. employees 2003	419	2693.39	19,104.49	1	365,571

Note: Revenue data are given in Mio. Euro and is measured in prices of 2000 (GDP market price deflator). Revenues give the value of annual sales of goods and services—including other types of revenue such as dividends, interest, and rent—of the respective company.

following, we employ a regression analysis in order to test whether the relative allocation (as measured by the allocation factor) had an impact on competitiveness as measured by firm revenues—here: representing the ''ability to sell'' as one concept of competitiveness[4]—and employment of the German firm sample. The related correlations are shown in Table A2. As dependent variables we use the firm revenue change in 2005, i.e. revenue 2005 minus revenue 2004, as an indicator of their ability to sell, and firm employment change in 2005, i.e. number of employees 2005 minus number of employees 2004. As it is common for an analysis with cross-sectional firm data and a continuous dependent variable (in both cases), we use ordinary least squares (OLS) in a first step in order to compute our regression results. Still, as lined out in the previous sections, the explanatory variable of our special interest in this analysis, the allocation factor, may be endogenous in such setting. This is due to the fact that its calculation is based on (verified) emissions from 2005 given that historic emission data are not publicly available. However, if revenue and/or employment development in 2005 had an impact on the respective emissions, reverse causality would render our estimation results from OLS biased and inconsistent. As the most common technical solution in such setting, additionally to OLS, we make use of the instrumental variable technique employing the so-called two-stage least squares estimator (2SLS). Doing this, in the regression equation of our interest (second stage), the possibly endogenous allocation factor is replaced by its fitted values from its (first stage) regression on exogenous variables (so-called instruments). As instruments for the allocation factor, firm data on revenues and employment in differences and levels are available besides sectoral variables that partly more strongly correlate with the allowance factor than the economic variables do. Furthermore, OLS results have been controlled for possibly outlier-driven results using so-called iteratively reweighted least squares (IRLS), the most common ''robust'' regression method. However, analogously to the OLS results, IRLS regressions may suffer from reverse causality problems. Given this fact (and the fact that our central results on relative allocation are consistent for all techniques applied), IRLS results are only displayed in Appendix A, and interpretation focuses on OLS and 2SLS.

4.2. Estimation results

The central results of the regression analysis are shown in Table 2 (Tables A3 and A4 give more detailed results). In the regression analysis (1) using revenue changes between 2005 and 2004 as a dependent variable, we include, besides the sectoral indicator variables and a constant term, the allocation factor as the explanatory variable of our major interest, as well as revenue differences 2004ffi2003, revenue differences 2003ffi2002, revenues 2003, the number of employees 2003, and the differences of the number of employees 2004ffi2003 as explanatory (control) variables. Using lagged levels and differences of revenues and employment as explanatory variables, we circumvent possible reverse causality or simultaneity (endogeneity) problems that can arise if the dependent variable has an influence on these explanatory variables.[5] Regression (3) gives the respective 2SLS results,

[4]As our empirical assessment focuses on the EU ETS, we refer to within-EU competitiveness among EU firms here (as opposed to international competitiveness vis-à-vis non-EU regions).

[5]In contrast to the allocation factor that we instrument in the 2SLS approach, these explanatory variables are incorporated in lagged form instead of being instrumented. Thereby we assume actual lagged relationships between the explanatory and independent variables.

Table 2
Selected regression results for German firm sample

Dep. var.	Revenues 2005ffi2004 (Mio. Euro)		No. employees 2005ffi2004	
Regression number/ estimation technique	(1) OLS	(3) 2SLS	(7) OLS	(9) 2SLS
Allocation factor	122.14 (110.72)	50,538.58 (42,836.84)	30.23 (119.04)	ffi44,067.80 (48,347.34)
No. obs.	419	419	419	419
R^2	0.84	0.84	0.85	0.85
F-test (p-val.)	0.00	0.00	0.00	0.00

Note: (White) robust std. errors in brackets. Results from regressions including the full set of control variables. Detailed results including parameter estimates of the control variable set (cp. regression numbers), as well as results of regression equations from which insignificant control variables have been eliminated and the IRLS estimations are given in Appendix A.

and (5) the IRLS results. From (2), (4), and (6), insignificant explanatory variables (besides the allocation factor) have been eliminated. For OLS and 2SLS, such elimination of insignificant explanatory variables is supported by an F-test. All in all, our results show a good fit of the econometric model, with an R^2 of 84%. According to the results of the F-test, the null hypothesis of joint insignificance of all explanatory variables can be rejected at the 1% level for any equation. The results, i.e. the parameter estimates of significant variables as well as their significance levels, are relatively robust to the choice of estimation technique as well as to the elimination of insignificant explanatory variables.

The main insight of this regression is that we do not find empirical evidence for a significant impact of the relative allocation of EU emissions allowances on firm revenue development in 2005. From a theoretical emissions-market perspective, a higher relative (grandfathered) allowance allocation induces lower compliance costs of emissions regulation (see e.g. Böhringer et al., 2005). Thus, relative allowance allocation and the subsequent trading of emissions permits affect the cash flow of the regulated firms. Clearly, the impacts of environmental regulation on firm revenues, production and employment are more complex and depend on the allocation rule (Demailly and Quirion, 2007). Our estimation results show a positive coefficient of the allocation factor both in the OLS and 2SLS regressions, which, given large standard errors, does not significantly differ from 0 in all equations presented in Table A3. Our results thus suggest that companies that received a relatively high amount of allowances within the allocation process could not, consequently, increase their revenues compared to other German companies within the emissions trading scheme. Besides the sectoral indicator variables that show a highly significant impact on revenue development, which can, for example, be explained by differences in sectoral demand, most other control variables do not show significance at any conventional level. An exception to this is the coefficient of the number of employees in 2003 that enters with a negative sign in the equation (with an estimated coefficient of about ffi0.20), suggesting that firms with a larger working force were less successful in increasing their revenues in 2005. IRLS gives partly different results, but, as indicated above, does not show any significance for the estimated coefficient of the allocation factor either.

In regression analysis (7) using the changes in the number of employees between 2005 and 2004 as a dependent variable, we include, besides the sectoral indicator variables and a constant term, the allocation factor as the explanatory variable of our major interest, as well as revenues 2004–2003, revenues 2003, the number of employees 2003, the number of employees 2004–2003, and the number of employees 2003–2002 as explanatory (control) variables. As in regression (1)–(6), the use of lagged levels and differences of revenues and employment as explanatory variables is due to the potential problem of endogeneity as well as of assumed lagged relationships (see footnote 4). Here as well, the results are robust to the elimination of insignificant explanatory variables and show a good fit of the econometric model, with an R^2 even slightly higher than in regression (1)–(4) (up to 85%). According to the results of the F-test, the null hypothesis of joint insignificance of all explanatory variables can be rejected at the 1% level for all approaches used. Regression (9) gives the respective 2SLS results, (11) the IRLS results. From (8), (10), and (12), insignificant explanatory variables (besides the allocation factor) have been eliminated (exclusion is supported by the F-test for the 2SLS and IRLS cases).

Analogously to the revenue analysis, we did not receive empirical evidence for a significant impact of the relative allocation of EU emissions allowances on the change in (firm level) employment in 2005. For regression (7) (as well as (11) and (12)), the estimated coefficient of the allocation factor is positive. However, the magnitude of the coefficient is small and is not significant at any conventional level. According to economic theory, stringent environmental regulation may induce employment losses if the output effect of regulation (i.e. lower production and employment levels) dominates the substitution effect (i.e. the shift to a higher labour intensity of production). Our estimation results suggest, however, that firms with a lower allocation factor within the trading scheme did not react with worker layoffs on a net basis.

In regressions (8)–(10), the sign of the estimated allocation factor coefficient changes (for IRLS, again, it

is positive in both regressions). However, the coefficients fail to show significance at any conventional level in all equations. In contrast to (1)–(6), the estimated coefficient of the number of employees 2004–2003 is—with a value of about 1—very high and negative. The coefficient, significant at the 1% level in each regression, suggests that the lay-off of workers in 2004 had a (similar) negative effect on the change of employment in 2005, i.e. the lay-off of one worker in 2004 resulted in the lay-off of an additional worker in 2005. This may be due to labour market rigidities as well as employment policies of the companies analyzed, provided that suspensions were relatively stable over time (2004–2005). Sectoral indicator variables have a highly significant impact on employment only using OLS. These results are therefore not very robust over the different econometric specifications, indicating that sectoral affiliation did not necessarily play a role in employment changes in 2005. Furthermore, the interpretation of the individual sectoral dummies is difficult, as the estimated parameters attribute the deviations of employment changes of the relative sector to those firms that formed part of sectors that were not explicitly modelled. Most other control variables fail to show significance at any conventional level. The effect of revenue as well as of employment development in 2004 on employment development in 2005 is extremely robust with regard to both point estimates and statistical significance. This undermines the findings of a positive relationship between 2004 revenue development and 2005 employment, as well as of a negative relationship between employment development in 2004 and 2005. At least as far as signs and significance of the estimated parameters are concerned, IRLS results resemble 2SLS.

5. Conclusions

This paper empirically investigates the role of the EU Emissions Trading Scheme (EU ETS) for competitiveness and employment at the firm level. We provide an overview over relative allowance allocation within the EU ETS, as well as an econometric analysis for a large sample of German ETS firms in order to assess the economic impacts associated with emissions allocation under the EU ETS.

Our calculations suggest that the total EU ETS was generally long in 2005. The long position is very large in Lithuania, while other countries were short in emissions allowances. Regarding the competitiveness effects of EU environmental regulation, we conduct an econometric ex-post regression analysis for Germany, which, to our knowledge, is the first of its kind concerning the EU ETS. Following the competitiveness concept ''ability to sell'', as an empirical indicator for competitiveness we employ firm revenues. As a second economic indicator we use employment levels of the respective firms. Our econometric analysis provides evidence on the fact that the allowance allocation within the EU ETS framework did not have a significant impact on revenues and employment of regulated German firms. Our results thus suggest that for regulated companies the competitiveness impacts of the emissions allocation within the first phase of the EU ETS were not pronounced. This finding could be due to the low overall burden of emissions regulation within the EU ETS.

Some disclaimers apply to these results. First, it is definitely very early to conduct an ex-post analysis for the EU ETS. In this respect, it is possible that competitiveness effects of this regulation could occur after 2005. Consistent economic firm data at a European level for 2005 or later were not available to us, so that our—first, and, due to the small dataset, basic—econometric analysis could only be performed within a case study for Germany, the most important country within the EU ETS according to the verified emissions. Furthermore, ex-post analyses do not have to be restricted to revenues and employment, although these are definitely two factors of great interest in the context of environmental regulation. Other measures of interest may be, e.g., innovation, profits, and international trade effects that could not be tackled within the analysis conducted here. All in all, future empirical research in many directions is needed to complement these first ex-post insights into the effects of regulation according to the EU ETS.

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Appendix A. Data on EU ETS allocation

Our analysis is based on data on approximately 12,000 installations being covered by the EU ETS legislation. Each installation has an Operator Holding Account in its national registry to which the allowances are submitted, and each member state of the European Union has an obligation to interlink the national registry with the

Table A1
Sectoral distribution of sample firms

Sector	Frequency: no. sample firms (%)
Mining	9 (2)
Electricity	55 (13)
Energy	29 (7)
Business	20 (5)
Pulp & paper	43 (10)
Coke & petroleum	8 (2)
Other manufacturing	102 (24)
Other	153 (37)
Total	419 (100)

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Table A2
Correlation analysis for German firm sample

	Allocation factor	Revenues 2005ffi2004	Revenues 2004ffi2003	Revenues 2005	No. employees 2005ffi2004	No. employees 2004ffi2003	No. employees 2005	Mining	Electricity	Energy	Business	Pulp & paper	Coke & petroleum	Other manufacturing
Allocation factor	1.00													
Revenues 2005ffi2004	0.01	1.00												
Revenues 2004ffi2003	ffi0.03	ffi0.36	1.00											
Revenues 2005	ffi0.02	ffi0.52	0.57	1.00										
No. employees 2005ffi2004	0.03	ffi0.22	ffi0.03	0.89	1.00									
No. employees 2004–2003	ffi0.02	0.06	0.43	0.35	0.19	1.00								
No. employees 2005	ffi0.01	ffi0.90	0.56	0.79	0.02	0.02	1.00							
Mining	0.03	0.02	0.01	0.04	0.03	0.03	ffi0.02	1.00						
Electricity	0.17	0.02	ffi0.06	ffi0.06	0.03	0.03	ffi0.04	ffi0.13	1.00					
Energy	0.02	0.01	ffi0.04	ffi0.04	0.02	0.02	ffi0.03	ffi0.09	ffi0.11	1.00				
Business	ffi0.03	ffi0.03	ffi0.03	ffi0.04	0.01	0.01	ffi0.02	ffi0.07	ffi0.09	ffi0.06	1.00			
Pulp & paper	ffi0.05	0.01	ffi0.04	ffi0.06	0.03	ffi0.03	ffi0.04	ffi0.05	ffi0.13	ffi0.09	ffi0.08	1.00		
Coke & petrol.	ffi0.04	ffi0.01	ffi0.02	ffi0.01	0.01	ffi0.01	ffi0.02	ffi0.02	ffi0.05	ffi0.04	ffi0.03	y0.05	1.00	
Other manuf.	ffi0.04	0.04	ffi0.04	ffi0.05	0.03	ffi0.05	ffi0.04	ffi0.08	ffi0.22	ffi0.15	ffi0.12	ffi0.19	ffi0.08	1.00

Note: 419 observations. Pearson's correlation coefficients for the respective variable pairs are given. Lagged levels and differences of higher order for the revenue and employment variables are omitted for brevity.

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EU-wide databank EU Community Transaction Log. The Community Transaction Log's web pages contain information on allowances that have been allocated in accordance with the final National Allocation Plans, verified emissions, surrendered allowances and compliance status for all installations in member states with registries. We assessed the emissions data from the Community Transaction Log in two steps:

- ffldata extraction from the Community Transaction Log and data processing; and
- fflaggregation of installation-level data on the sectoral and national levels.

A.1. The AMADEUS database

Besides the emissions data from the Community Transaction Log, economic data are of great importance for assessing the competitiveness effects of the EU ETS. AMADEUS (Analyse Major Databases from European Sources) is a comprehensive, pan-European database containing economic and financial information on 9 million public and private companies. AMADEUS combines data from over 30 specialist sources and provides data in a comparable format. It is created and produced by Bureau van Dijk. In this analysis, sectoral information for our German firm sample is based on the four-digit NACE (industry) codes of the firms provided by AMADEUS. According to this, we have created several indicator variables that are given the value 1 for a company that forms part of the respective industry, and 0 otherwise. The indicator variables are ''electricity'' (13% of the sample firms; NACE code between 4000 and 4020, ''production and distribution of electricity''), ''energy'' (7% of the sample firms; NACE code between 4020 and 4500, ''manufacture of gas; distribution of gaseous fuels through mains'', ''steam and hot water supply'', ''collection, purification and distribution of water''), ''pulp & paper'' (10% of the sample firms; NACE code between 2100 and 2200, industry subsection ''manufacture of pulp, paper, and paper products''), ''mining'' (10% of the sample firms; NACE code between 1000 and 1500, industry subsection ''mining and quarrying''), ''coke & petroleum'' (2% of the sample firms; NACE code between 2300 and 2400, ''manufacture of coke, refined petroleum products and nuclear fuel''), ''other manufacturing'' (24% of the sample firms; NACE code between 2600 and 3700, manufacture of

Table A3
Regression results on 2005 revenue development for German firm sample

Dep. var.	(1) OLS	(2) OLS	(3) 2SLS	(4) 2SLS	(5) IRLS	(6) IRLS
	Revenues 2005ffi2004 (Mio. Euro)	Revenues 2005ffi2004 (Mio. Euro)	Revenues 2005ffi2004 (Mio. Euro)	Revenues 2005ffi2004 (Mio. Euro)	Revenues 2005ffi2004 (Mio. Euro)	Revenues 2005ffi2004 (Mio. Euro)
Allocation factor	122.14 (110.72)	83.72 (117.58)	50,538.58 (42,836.84)	1552.76 (2140.87)	ffi0.33 (0.75)	ffi0.36 (0.76)
Revenues 2004ffi2003 (Mio. Euro)	ffi0.03 (0.66)	–	0.01 (1.25)	–	0.22*** (0.00)	0.21*** (0.00)
Revenues 2003ffi2002 (Mio. Euro)	0.01 (0.18)	–	ffi0.30 (0.84)	–	ffi0.02*** (0.00)	ffi0.02*** (0.00)
Revenues 2003 (Mio. Euro)	ffi0.05 (0.18)	–	1.24 (1.72)	–	0.03*** (0.00)	0.03*** (0.00)
No. employees 2003	ffi0.18*** (0.07)	ffi0.19*** (0.03)	ffi0.66 (0.64)	ffi0.19*** (0.03)	0.00*** (0.00)	–
No. employees 2004–2003	0.15 (0.11)	–	0.34** (0.14)	–	0.00*** (0.00)	–
Mining	ffi225.89 (255.96)	–	338.81 (6456.00)	–	6.21** (2.99)	5.58* (2.95)
Electricity	ffi483.89*** (134.43)	ffi471.20*** (112.97)	ffi8980.94 (11737.64)	–	7.61*** (1.39)	7.07*** (1.30)
Energy	ffi491.44*** (128.93)	ffi488.11*** (105.70)	ffi3335.58 (5964.47)	ffi443.98** (212.50)	4.92*** (1.76)	4.17** (1.70)
Business	ffi1083.73** (529.95)	ffi1085.56* (598.66)	5823.88 (6566.77)	–	1.28 (2.08)	–
Pulp & paper	ffi482.81*** (116.57)	ffi478.65*** (100.03)	2020.76 (3730.35)	ffi293.81* (155.56)	0.39 (1.51)	–
Coke & petroleum	ffi836.93* (479.15)	ffi878.94* (469.98)	5482.63 (7324.90)	–	7.61** (3.15)	8.07*** (3.15)
Other manufacturing	ffi181.27 (192.49)	–	423.98 (3146.08)	–	1.38 (1.12)	–
Constant term	436.91*** (152.38)	475.14*** (164.28)	ffi61,101.61 (51,916.09)	ffi1431.85 (2611.28)	ffi3.17*** (1.18)	ffi2.44** (1.05)
No. obs.	419	419	419	419	413	414
R^2	0.84	0.80	0.84	0.82	–	–
F-test (p-val.)	0.00	0.00	0.00	0.00	0.00	0.00
F-test on excl. exp. var. (p-val.)	–	0.50	–	0.29	–	0.00

Note: Std. errors in brackets (OLS, 2SLS: white robust std. errors). *, ** and *** show significance at the 10%, 5%, and 1% levels, respectively.

Table A4
Regression results on 2005 employment development for German firm sample

Dep. var.	(7) OLS	(8) OLS	(9) 2SLS	(10) 2SLS	(11) IRLS	(12) IRLS
	No. employees 2005ffi2004	No. employees 2005ffi2004	No. employees 2005ffi2004	No. employees 2005ffi2004	No. employees 2005ffi2004	No. employees 2005ffi2004
Allocation factor	30.23 (119.04)	ffi12.00 (62.79)	ffi44,067.80 (48347.34)	ffi8126.44 (9355.91)	0.49 (2.04)	0.40 (2.21)
Revenues 2004ffi2003 (Mio. Euro)	4.58*** (0.71)	4.29*** (0.70)	4.43*** (0.93)	4.38*** (0.62)	0.02*** (0.01)	0.02*** (0.01)
Revenues 2003 (Mio. Euro)	0.05 (0.28)	–	ffi0.71 (1.38)	–	0.00** (0.00)	–
No. employees 2003	ffi0.05 (0.11)	–	0.22 (0.52)	–	0.00*** (0.00)	ffi0.02*** (0.00)
No. employees 2004ffi2003	ffi1.00*** (0.04)	ffi1.01*** (0.04)	ffi1.15*** (0.16)	ffi1.05*** (0.05)	ffi1.00*** (0.00)	ffi1.01*** (0.00)
No. employees 2003ffi2002	ffi0.85 (0.80)	–	ffi1.40 (1.98)	–	0.00 (0.00)	–
Mining	486.99 (316.47)	373.76* (193.43)	323.98 (5404.09)	–	ffi4.86 (8.01)	–
Electricity	562.16* (307.10)	431.50** (183.63)	8032.52 (11732.76)	–	0.62 (3.76)	–
Energy	576.89** (280.85)	460.36*** (178.56)	3036.61 (5619.92)	–	9.57** (4.77)	–
Business	555.29* (315.56)	394.59* (228.14)	ffi4859.04 (6423.88)	–	6.85 (5.62)	–
Pulp & paper	565.95* (320.64)	432.77** (186.05)	ffi1540.41 (3394.63)	–	ffi0.62 (4.07)	–
Coke & petroleum	624.19** (273.35)	512.96*** (192.22)	6473.68 (7243.06)	–	11.07 (8.56)	–
Other manufacturing	285.82 (365.37)	–	ffi235.53 (2741.93)	–	4.31 (3.02)	–
Constant term	ffi642.96* (388.52)	ffi467.25** (198.56)	53,153.02 (58,410.43)	9668.14 (11,335.02)	ffi3.32 (3.17)	4.37 (3.03)
No. obs.	419	419	419	419	415	416
R^2	0.85	0.83	0.85	0.35	–	–
F-test (p-val.)	0.00	0.00	0.00	0.00	0.00	0.00
F-test on excl. exp. var. (p-val.)	–	0.00	–	0.96	–	0.21

Note: Std. errors in brackets (OLS, 2SLS: white robust std. errors). *, ** and *** show significance at the 10%, 5%, and 1% levels, respectively.

non-metallic mineral products, basic metals and fabricated metal products, machinery and equipment, electrical and optical equipment, transport equipment, other manufacturing), and ''business'' (5% of the sample firms; NACE code between 7000 and 7500, section ''real estate, renting, and business activities'').

A.2. The CREDITREFORM database

This database is a financial and economic database that includes information of sales and employment of German firms. It is the most comprehensive database on German firms, containing a random sample of 20,000 solvent and 1000 insolvent firms in Germany. Given a consistent form identification number, it is coherent with the AMADEUS database. From the CREDITREFORM database we use levels and differences from firm revenue and employment data between 2002 and 2005; from AMADEUS we use generated sectoral indicator variables (see above). Those data have been matched with the allocation factor (allowances allocated divided by verified emissions) from the Community Transaction Log. This has been conducted by supplementing allocation data that have been aggregated at the firm level with AMADEUS and CREDITREFORM data. The main criteria for this database matching were the respective company names and addresses. The matching results have been carefully checked for consistency reasons (Tables A1–A4).

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Climate Policy and Corporate Behaviour

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Abstract: In this paper, we study the impact of energy taxes and the EU ETS on a large number of firms in Europe between 1996 and 2007. Using company level micro-data, we examine how firms in different sectors were affected by environmental policies. Aspects of behaviour and performance studied include total factor productivity, employment levels, investment behaviour and profitability. On the whole, energy taxes increased total factor productivity and returns to capital but decreased employment, with a mixed effect on investment, for the sectors included in our analysis. However, large sectoral variation is observed, with some industries losing out in terms of productivity and profitability when faced with increased energy taxes, while others benefitted.

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Key words: energy taxes, productivity, investment, firm performance

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Climate Policy and Corporate Behaviour

1. Introduction

With increasing emphasis on environmental regulation in the industrial sector in recent years, it is important to understand the impacts of such measures on firm productivity and investment behaviour. While much attention has been focused on the environmental benefits of differing climate policies, there is relatively little empirical evidence of their impact on company behaviour.

In this paper, we are interested in the effect of energy and carbon taxes on various measures of corporate behaviour and performance. Using firm level micro-data, we focus on the influence of these taxes on the employment levels, investment behaviour and productivity of European companies for the years 1996 to 2007.

Theory provides conflicting guidance as to the likely effects of environmental regulation and taxes on firm behaviour and performance. Taxes represent additional costs for a firm, and as such would be expected to be a constraint on their production possibilities and thus reduce profits. However, when faced with higher environmental taxes, firms may seek to reduce their costs by locating in "pollution havens" or countries where environmental standards or regulatory costs are relatively low. This is known as the pollution haven hypothesis.

Other models stress the importance of the availability of clean natural resources as factor inputs, which could help to improve the production possibilities of firms (factor endowment hypothesis). Equally, technology innovation as a result of increased regulation is also considered a potential outcome. According to the Porter Hypothesis (Porter 1991; Porter & van der Linde 1995), environmental regulation provides incentives for companies to innovate, which can increase competitiveness and productivity. Both the factor endowment and Porter Hypotheses imply that environmental stringency may lead to improvements in the performance of firms as well as advancing environmental goals (Wagner 2003)

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There is also some previous empirical research into the impact of environmental regulation on company behaviour and performance. Leiter *et al.* (2009) study firm investment decisions in response to environmental protection measures. Using European industry-level panel data, they find a positive but diminishing impact of environmental stringency on investment. Average elasticities of around 0.15 for industry expenditure on environmental protection and 0.06 for country revenue from environmental taxes are found.

Veith *et al*. (2008) examine the impact of the EU ETS on capital market responses in the power generation sector. Returns on common stock in this sector are found to be positively correlated with rising prices for emissions rights. This indicates that the ETS increases profits, as firms pass on or even overcompensate for regulation costs in prices charged to customers, thus increasing their profitability.

A study undertaken as part of the EU COMETR study, Enevoldsen (2007), includes an analysis of eight sectors in seven European countries. The results show a slightly negative effect of energy taxes on competitiveness and output. However, Henderson and Millimet (2005), using a US sample, find insignificant effects of environmental stringency on state-level output.

While most of the previous literature is undertaken at country or industry level, there has been relatively little research undertaken using firm level micro-data. Anger and Oberndorfer (2008) assess the impact of the EU ETS on firm performance and employment. Using a sample of German firms, they do not find an effect of the relative allocation of emission allowances on firm revenue and employment in 2005. Martin *et al.* (2009) investigate the effect of a UK energy tax, the climate change levy, on the manufacturing sector using firm panel data. However, they find no significant impacts on employment, gross output or total factor productivity (TFP).

Economic theory and previous empirical research suggests conflicting or ambiguous outcomes of environmental policies on corporate performance. The pollution haven hypothesis would suggest decreased employment in more stringently regulated sectors, and the assumption that taxes cause additional cost burdens on firms would

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equally point to decreased productivity and profitability. However, the Porter Hypothesis and Factor Endowment theory suggest otherwise. They indicate the potential for increased output and TFP due to the availability of clean natural resources, or to increased innovation.

However, we can see from previous empirical work that these findings vary widely, based on which sectors and countries are included in the analysis. The literature finds conflicting or insignificant results for competitiveness, employment and investment amongst different country and industry samples. The type of regulation is also important to take into consideration, as energy taxes are expected to be more efficient than some other forms of regulation, such as command-and-control approaches. For this reason it is important to utilise data at the most disaggregated firm level, and to undertake cross-country and cross-industry analysis in order to examine the validity of these conflicting viewpoints.

In this paper, we make use of cross-country firm level panel data, for a large sample of European companies. In order to test the differing hypotheses, we examine how firms in different industries adapt their structure and behaviour in response to energy taxes and the introduction of the EU Emissions Trading Scheme. We assess the effects of such environmental policies on employment, investment and productivity over a twelve year period.

2. Data

The data employed in this paper is firm-level panel data for a range of European firms across various sectors, provided in the AMADEUS database. This database contains financial and economic information for approximately 11 million firms across Europe. The dataset we used covered the years 1996 to 2007.

From this we construct four dependent variables, representing several measures of corporate performance. These include:

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- Total Factor Productivity (TFP)
- Number of employees
- Investment (calculated as change in tangible fixed assets minus depreciation)
- Return on capital employed

While our main data source is the Amadeus database, additional industry and country level variables are collected from a range of sources, such as the OECD, Eurostat and the International Energy Agency.

Energy tax data is sourced from the Eurostat environmental accounts. These consist of taxes on energy products such as petrol, diesel, fuel oils, natural gas, coal and electricity. CO_2 taxes are also included where applicable. Both energy taxes at time *t*, as well as lagged energy taxes, are incorporated into each model. Firms covered under the EU Emissions Trading Scheme are indicated by a binary variable, given a value of 1 for all sectors included in the scheme since its introduction in 2005, and 0 for all other sectors.

In addition, labour cost shares at country level, calculated as total country labour costs as a proportion of output, are collected from the OECD and included as independent variables in both the employment and TFP models. Other determinants of TFP are also included as controls. Educational attainment at country level (the proportion of people aged 25-64 with a third level education), national output gap, and the import intensity of each industry were obtained from the OECD. Electricity prices per country, from the International Energy Agency, are also included.

We use TFP as our productivity measure since changes in TFP directly reflect efficiency gains due to the reorganization of production processes (Factor Endowment Hypotheses) as well as the introduction of new technologies or innovations related to improvements of a firm's energy efficiency (Porter Hypotheses). We derive TFP of firm *j* in sector *s* at time *t* as a residual from a production function in logs:

$$y_{jst} = \beta_s^k k_{jst} + \beta_s^l l_{jst} + \alpha_i + \eta_s + \mu_t + \varepsilon_{jst} \qquad (2)$$

where y_{jst} denotes a firm's real value added, k_{jst} the real physical capital stock and l_{jst} the labour input, α_i is a vector of country specific effects, η_s a vector of

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industry specific effects, μ_t a vector of year specific effects, $\beta = (\beta^k \beta^l)$ a vector of average input elasticities, and ε_{jst} an error term.[1]

We estimate (2) to obtain empirical measures of the average input elasticities β from firm level data. We account for heterogeneous input elasticities across three-digit (NACE) industry levels in that we estimate the marginal input effects separately for each of the three-digit industries. Note, however, that we pool the observations in each three-digit industry across countries in order to obtain sufficient information for robust production function estimations per industry. We believe that this is a relatively minor restriction on the data since average input elasticities for three-digit industries are typically found to be relatively homogeneous across European countries. Obtaining the estimates for the average input elasticities for each three-digit industry allows us, together with the information on *y*, *k*, and *l* of each individual firm, to compute residual TFP measures at the firm-level. However, the estimation of (2) involves an endogeneity problem which is well-known in the literature on production functions estimation. That is, a firm's demand for labour is expected to depend on its contemporaneous productivity level which is unobserved and hence captured in the error term. In such a case, the estimated input elasticities would be biased. Appropriate instruments for labour services that are uncorrelated with productivity are typically not available. Being aware of this problem, we consistently estimate (2) following Olley and Pakes (1996) who propose a semi-parametric estimator to correct for this simultaneity bias by imposing additional restrictions on the data. In particular, the authors use changes in firm's investment decision as a proxy for the productivity shock. The method supposes that a firm's investment decision is a function of its capital stock, age, and its unobserved productivity. Hence, the unobserved productivity parameter can be modeled as some (inverse) function of investments, capital, and age given the assumption of a monotonic relationship between investment and productivity. We apply this methodology to derive consistent estimates of the average input elasticities in our sample.

Variable definitions and sample means are presented in Tables 2 and 3 below.

[1] Real variables are obtained deflating by the national output price deflators. Unfortunately, price deflators were not available at the industry level for most of the countries.

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3. Methodology

We have estimated four models, each exploring a different aspect of company behaviour or performance. First, our model of employment tests the suggestion that these taxes weaken the incentive to use capital due to high energy-capital complementarity, with firms switching to more labour-intensive activities. However, decreased employment may also be observed in heavily regulated sectors, as firms seek to minimise their costs by moving towards countries or industries with lower levels of stringency. Labour costs are included in this model, to control for differing labour costs across countries over time, which may otherwise be driving the change in a firm's number of employees.

Total factor productivity measures the component of output that arises from factors other than capital and labour. This is often regarded as the impact of technology innovation on firm performance. In this case, energy taxes may have a positive or negative effect, depending on which of the previously outlined theories of environmental regulation are seen to hold. This model controls for additional TFP determinants such as education levels, the gap between actual and potential GDP (output gap), and the import intensity of the specific sector. While import intensity and education, representing higher human capital levels, would be expected to increase TFP, we expect the output gap variable to have a negative sign. Although firms may be expected to innovate and reorganise when operating in a country with an increasing output gap, there may be a loss of knowledge capital in such countries, which tend also to have high unemployment levels. Moreover, some forms of labour input that tend to increase in a capacity-constrained economy (e.g. overtime working) may be omitted from the measure of labour inputs and thereby boost TFP when the output gap is shrinking. On balance, these effects are likely to imply that increasing the output gap will negatively influence firms' TFP levels. Electricity prices are also included and are expected to have a negative effect on TFP.

Return on capital employed is included as a profitability indicator. Energy taxes would be expected to decrease profitability under the assumption that taxes act as an additional costs on doing business. Finally, our fourth company behaviour variable is

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investment. If energy taxes have similar effects to taxes on capital, there would be an expected negative sign on these coefficients in the investment model, as firms substitute capital for labour. The pollution haven hypothesis also points towards negative effects on investment. However, the Porter Hypothesis would suggest that firms facing increased regulation would have an incentive to innovate and invest in new technology in order to improve productivity. This would suggest increases in investment due to energy taxes. However, it is necessary to empirically examine these in further detail in order to test the competing theoretical stories.

In order to control for unobserved time- and company-specific heterogeneity, we use panel regression analysis. We allow for sectoral variations in energy tax effects by including sector-tax interaction terms for energy tax levels and lagged tax levels.

Many of the variables included exhibit some intertemporal persistence or are non-stationary (e.g. investment, employment), so estimating the models in levels would be expected to lead to substantial residual serial correlation. To avoid this, we estimate the regressions in first differences. The coefficients may thus be viewed as representing equilibrium values.

4. Results

Since the focus of interest for this research is on tax effects, we first present estimates of the tax effects by sector for each model. Later in the section we discuss other explanatory variables.

Tax effects

Sectoral variations in tax effects feature prominently in all four models. These are calculated for each sector by adding the tax coefficients and the tax-sector interaction coefficients for both the current period and lagged taxes. The results for TFP are shown in Figure 1 below. The figure shows the percent change in the TPF growth rate for each sector associated with a 1% tax increase. Thus a 10% tax increase would be associated with a 10% fall in the TFP growth rate for the tobacco sector. If TFP in

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this sector would otherwise grow by 2%, this implies a lower growth rate of 1.8% due to the tax change.

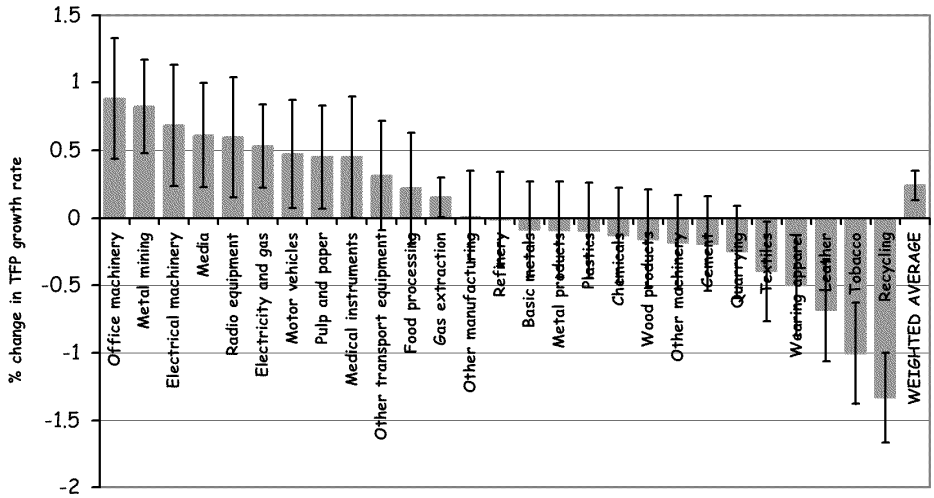

Figure 1: Average partial effect of 1% rise in energy taxes on TFP growth by sector

TFP growth is positively associated with energy taxes in some sectors, but reduced in others. This provides some evidence for Porter Hypothesis effects, but only for selected sectors. Primary resource sectors such as coal, metal, oil and gas extraction benefited from higher TFP growth, along with a range of manufacturing sectors producing energy-using goods (e.g. office machinery, electrical machinery, radio equipment). Electricity and gas generation and the media sector also showed a positive effect. Many sectors showed no statistically significant effect (standard errors were relatively high in this model), but wearing apparel, leather, tobacco and recycling showed a negative association with energy taxes. The average effect of a tax change on TFP growth, weighting sectoral effects by the output shares of these sectors in Europe, is positive.[2] This suggests that *ceteris paribus* a marginal tax increase would lead to a small but statistically significant improvement in TFP growth for these sectors in Europe.

[2] The sector shares were obtained from the OECD STAN database.

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The relationship between energy taxes and employment for different sectors is set out in Figure 2 below.

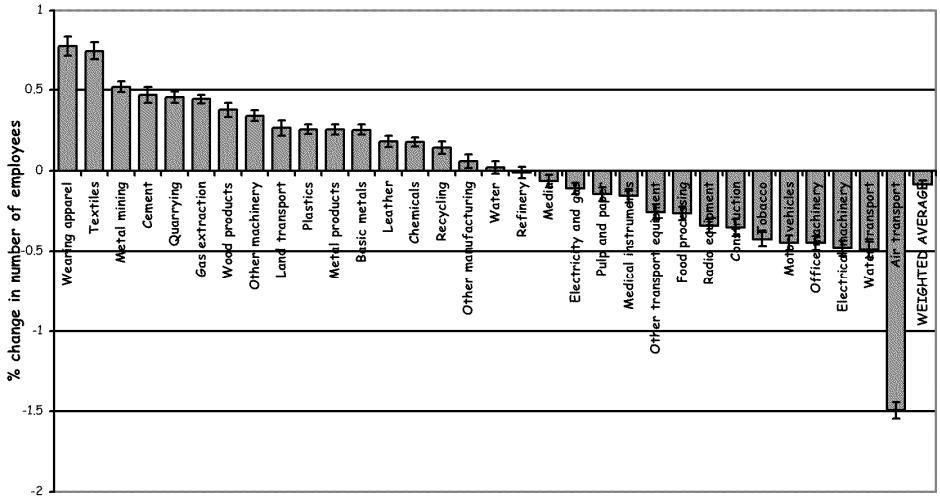

Figure 2: Average partial effect of 1% rise in energy taxes on firms' employment by sector

In this case, standard errors are much lower and most sectors exhibit a significant effect. Some sectors show a positive employment effect relating to energy taxes; notably wearing apparel, textiles, and primary resource sectors. Air transport shows a strongly negative association, with a 10% tax rise being associated with a 15% reduction in employment. Other sectors exhibit weaker positive or negative effects. In this case, the average effect (weighted by sectoral employment shares in Europe) is negative. Overall, then, a marginal increase in energy taxes is associated with lower employment for this set of sectors in Europe.

Air transport also features a large and significant effect in relation to corporate investment (Figure 3 below). In this case the effect is positive, with a hypothetical 10% tax rise being associated with a 20% increase in fixed investment. Basic metals, refining and water transport also have relatively large positive coefficients, while tobacco has a very large negative association and the recycling and leather sectors have smaller negative coefficients. The average effect, weighted by total sectoral investment, is not significantly different from zero. This implies that energy taxes at

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the margin do not have a statistically significant effect on total investment levels in this sample.

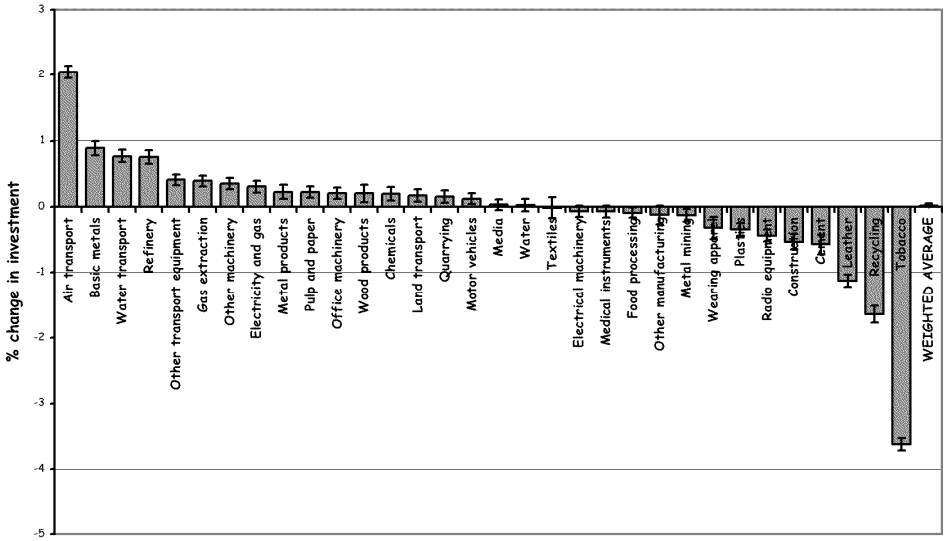

Figure 3: Average partial effect of 1% rise in energy taxes on firms' investment by sector

Our final model examined the association between energy taxes and company profitability, proxied by the return on capital employed. This relationship proves to be positive in most cases, with the strongest relationship being for air transport. Only a few sectors – water transport, refining, wood products, coal and peat extraction, food processing and quarrying having significant negative coefficients. The average effect, weighting sectoral effects by the output shares of these sectors in Europe, is positive and statistically significant. This suggests that a marginal increase in energy taxes would increase profitability on average.

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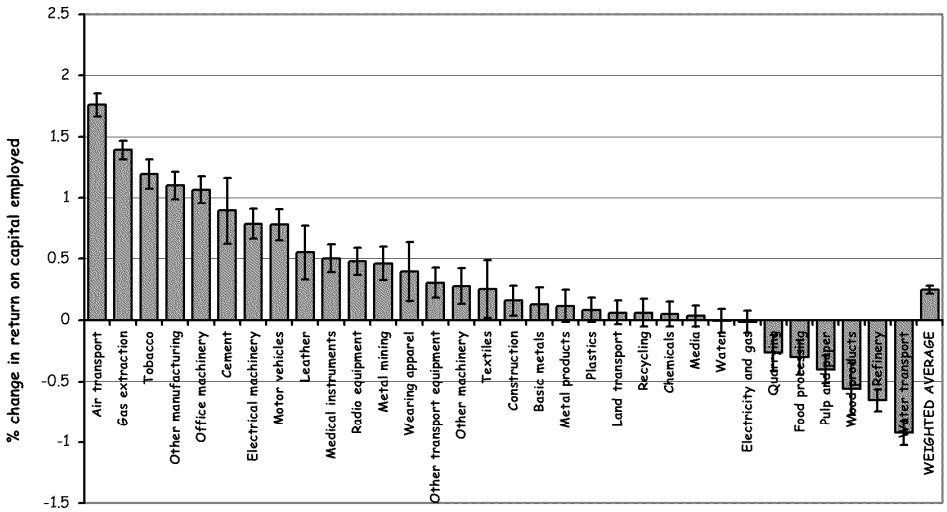

Figure 4: Average partial effect of 1% rise in energy taxes on firms' return on capital employed by sector

We considered whether the sectoral pattern of energy tax effects shown above might be driven by broader sectoral characteristics such as energy intensity or technology intensity. However, grouping sectors by these classifications did not reveal any obvious association with the tax effects. The impact of energy taxes on TFP, employment, investment and profitability vary by sector even amongst industries which have similar energy and technology use.

Other effects

Since we have estimated these models in differences, we only observe effects for factors that vary over time. All models allow for ETS participation effects, and the relevant coefficients are shown in Table 1 below. We find no significant association between ETS participation and employment or investment. However, both TFP growth and return on capital employed were lower in ETS participant firms, *ceteris paribus*. For a firm with a TFP growth rate of 2%, participation in the ETS would be associated with 0.12% lower TFP growth.

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Table 1: ETS participation effects

Dependent variable	ETS effect	Robust standard error
TFP growth	-0.0616***	0.0196
ln(employment)	0.0173	0.0142
ln(investment)	0.00161	0.0249
ln(Return on capital employed)	-0.0673***	0.0185

Lower productivity and profitability among ETS firms is consistent with the view that the scheme increased firms' costs without inducing significant Porter Hypothesis effects. With the dataset we are using here, it is not possible to tell whether a different design or level of stringency for the ETS would have changed this conclusion.

Finally, we can report a range of secondary results. In the TFP model, sectoral import intensity, national education level and labour costs were not significant (we had expected the first two factors to have a positive effect on TFP and the third to have a negative effect). Labour cost was, as expected, negative and highly significant in the employment model. Returning to the TFP model, the output gap and electricity prices both showed highly significant negative effects, which was in line with our expectations.

5. Conclusions

In this paper, we study the impact of energy taxes and the EU ETS on a large number of firms in Europe between 1996 and 2007. To the best of our knowledge, we are the first to do so. We estimate the effect on the change in total factor productivity (a proxy for technological progress), on employment, on investment, and on the returns to capital (a proxy for accounting profits). The following results emerge. First, as one would expect, results vary dramatically between sectors, not just in the size of the estimated effects but also in their signs. Second, total factor productivity accelerates with higher carbon taxes. Although the effect is insignificant in large parts of the economy, and negative in some sectors, the positive impact in a number of sectors dominates. This finding supports the Porter Hypothesis. Regulation spurs innovation. Third, energy taxes reduce employment. There is a significant impact on employment

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in almost all sectors. The most important effect is a large shift in labour between sectors, but the overall effect is negative. While energy taxes create jobs, more jobs are destroyed. Fourth, energy taxes increase investment. The impact is again significant in most sectors, and the most notable effect is a shift in investment between sectors. The aggregate effect is positive, however. This suggests that businesses respond to energy taxes by substituting labour for capital. This is in sharp contrast to the findings by Koetse et al. (2008). Fifth, energy taxes increase the returns to capital. Again, differences between sectors are pronounced, but the average effect is positive. This finding reinforces the results for investment.

We obtain different results for the EU ETS. The effect on productivity and profits are negative, while the effect on labour and investment are insignificant. These results are indicative only, as our data only cover the experimental phase of the ETS and we were unable to define a permit price. Future research, using data from the second phase of the ETS, should reinvestigate this.

Acknowledgments

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Tables

Table 2: Variable definitions

Dependent variables		**Independent variables**	
Total Factor Productivity (lnTFP)	Olley-Pakes method. Log TFP in first differences	Tax rate (lntax_rate)	Log of energy taxes by sector and country, first differences. Includes taxes on petrol, diesel, gas, electricity etc.
Employment (lnL)	Log number of employees in a firm in year t, in first differences.	Lagged Tax rate (lntax_rate t-1)	Log of energy taxes, 1 period lag. First differences.
Return on Capital Employed	Return on capital employment in year t, in first differences	Import Intensity	Imports/ (Production – Exports + Imports)
Investment	Log change in tangible fixed assets minus depreciation, in first differences	Education	Tertiary education attainment for age group 25-64, as a percentage of the population of that age group in each country.
		Output Gap	Deviations of actual GDP from potential GDP as a percentage of potential GDP
		Electricity price (ln elec price)	Electricity prices per country (€ per kWH)
		Labour Cost	Total Labour Costs as a percentage of Output, per country
		ETS	Emissions Trading Scheme dummy variable, 1 if sector covered by ETS, 0 otherwise

Table 3: Variable means

	TFP	**Employment**	**Return On Capital Employed**	**Investment**
Independent Variables	227942 obs.	649809 obs.	506682 obs.	427483 obs.
Tax rate	0.004	0.003	0.004	0.004
Lagged Tax rate	0.004	0.003	0.004	0.004
Labour Cost	0.589	0.623		
Education	19.742			
Output Gap	-0.093			
Electricity price	0.070			
Import Intensity	0.277			

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Annex A: Regression results

Table 4: Total factor productivity regression results, OLS panel regression in first differences; dependent variable: ln(TFP_{it})

Variables and statistics	Coef.	Robust standard error
Ltax_rate	0.935***	0.109
Ltax_rate-1	0.257***	0.0539
import_intensity	0.0268	0.0228
education	-0.0552	0.0331
output_gap	-0.166***	0.0568
Lelectricityprice	-0.129***	0.0382
labourcost	-1.77	2.9
ETS	-0.0616***	0.0196
NACExTax11	-1.04***	0.00638
NACExTax13	-0.371***	0.104
NACExTax14	-1***	0.104
NACExTax15	-1.01***	0.0808
NACExTax16	-2.95***	0.0588
NACExTax17	-1.04***	0.121
NACExTax18	-1.09***	0.12
NACExTax19	-1.49***	0.127
NACExTax20	-0.956***	0.118
NACExTax21	-0.79***	0.0732
NACExTax22	-0.63***	0.0751
NACExTax23	-0.823***	0.106
NACExTax24	-0.956***	0.108
NACExTax25	-0.945***	0.109
NACExTax26	-0.97***	0.108
NACExTax27	-0.924***	0.11
NACExTax28	-0.926***	0.111
NACExTax29	-0.963***	0.107
NACExTax30	-0.795***	0.112
NACExTax31	-0.631***	0.115
NACExTax32	-0.782***	0.111
NACExTax33	-0.875***	0.116
NACExTax34	-0.804***	0.0696
NACExTax35	-0.688***	0.071

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Variables and statistics	Coef.	Robust standard error
NACExTax36	-0.974***	0.0966
NACExTax37	-1.72***	0.09
NACExTax40	-0.655***	0.0765
NACExTax14	-0.443***	0.0117
NACExTax15	0.0366	0.266
NACExTax16	0.753***	0.258
NACExTax17	-0.554***	0.0529
NACExTax18	-0.597***	0.0528
NACExTax19	-0.391***	0.0374
NACExTax20	-0.391***	0.0383
NACExTax21	0.0464	0.235
NACExTax22	0.0475	0.236
NACExTax23	-0.378***	0.0417
NACExTax24	-0.363***	0.0317
NACExTax25	-0.34***	0.0257
NACExTax26	-0.413***	0.0495
NACExTax27	-0.351***	0.0241
NACExTax28	-0.355***	0.0236
NACExTax29	-0.407***	0.0268
NACExTax30	0.482*	0.266
NACExTax31	0.121	0.262
NACExTax32	0.185	0.261
NACExTax33	0.131	0.26
NACExTax34	0.0835	0.273
NACExTax35	-0.191	0.275
NACExTax36	-0.211***	0.0747
NACExTax37	-0.802***	0.0677
NACExTax40	-0.00815	0.0479
D1998	0.378***	0.0983
D1999	0.363***	0.103
D2000	0.359***	0.117
D2001	0.168***	0.0498
D2003	-0.0209*	0.0103
D2004	0.178***	0.0634
D2005	-0.0453*	0.0232
Constant	-0.0438**	0.016

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Variables and statistics	Coef.	Robust standard error
Sample	65,787 firms	
Observations	227,942	
Min. periods	1	
Avg. periods	3.5	
Max. periods	7	
R^2 within	0.0156	
R^2 between	0.0004	
R^2 overall	0.0077	

*Note: All variables are in first differences apart from the constant, and variables with an L prefix are in log terms. *, ** and *** denote significant at the 10%, 5% and 1% level respectively. t-statistics are heteroscedasticity-robust and allow for clustering at sector level.*

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Table 5: Employment regression results, OLS panel regression in first differences, dependent variable: ln(employment$_{it}$)

Variables and statistics	Coef.	Robust standard error
Ltax_rate	0.299***	0.0234
Ltax_rate-1	-0.062***	0.0113
labourcost	-2.29***	0.296
ETS	0.0173	0.0142
NACExTax11	-0.294***	0.00741
NACExTax13	-0.172***	0.013
NACExTax14	-0.0279	0.0178
NACExTax15	-0.328***	0.0242
NACExTax16	0.434***	0.0242
NACExTax17	0.0702**	0.0333
NACExTax18	0.0421	0.0368
NACExTax19	-0.162***	0.0127
NACExTax20	-0.224***	0.014
NACExTax21	-0.297***	0.0223
NACExTax22	-0.35***	0.0236
NACExTax23	-0.329***	0.021
NACExTax24	-0.222***	0.00984
NACExTax25	-0.168***	0.00964
NACExTax26	-0.0538*	0.0301
NACExTax27	-0.199***	0.00909
NACExTax28	-0.211***	0.00932
NACExTax29	-0.171***	0.0112
NACExTax30	-0.504***	0.0206
NACExTax31	-0.648***	0.0221
NACExTax32	-0.671***	0.0198
NACExTax33	-0.429***	0.0205
NACExTax34	-0.616***	0.0255
NACExTax35	-0.379***	0.0265
NACExTax36	-0.29***	0.0246
NACExTax37	-0.315***	0.0228
NACExTax40	-0.358***	0.0218
NACExTax41	-0.355***	0.0239
NACExTax45	-0.583***	0.0308
NACExTax60	-0.271***	0.0287
NACExTax61	-0.659***	0.029

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Variablcs and statistics	Cocf.	Robust standard crror
NACExTax62	-0.861***	0.0299
NACExTax11	0.501***	0.00686
NACExTax13	0.455***	0.0167
NACExTax14	0.246***	0.0158
NACExTax15	-0.172***	0.0237
NACExTax16	-1.1***	0.0231
NACExTax17	0.439***	0.0382
NACExTax18	0.5***	0.0395
NACExTax19	0.106***	0.0166
NACExTax20	0.364***	0.0301
NACExTax21	-0.0845***	0.0229
NACExTax22	0.0489***	0.0148
NACExTax23	0.0806***	0.00946
NACExTax24	0.163***	0.00866
NACExTax25	0.189***	0.00898
NACExTax26	0.287***	0.0274
NACExTax27	0.216***	0.0132
NACExTax28	0.23***	0.0129
NACExTax29	0.275***	0.0139
NACExTax30	-0.18***	0.0276
NACExTax31	-0.0673**	0.0297
NACExTax32	0.0927***	0.027
NACExTax33	0.0369	0.0272
NACExTax34	-0.0669**	0.0284
NACExTax35	-0.112***	0.0293
NACExTax36	0.113***	0.0245
NACExTax37	0.222***	0.0175
NACExTax40	0.0121	0.0126
NACExTax41	0.139***	0.0101
NACExTax45	-0.00434	0.0342
NACExTax60	0.299***	0.0304
NACExTax61	-0.0668**	0.031
NACExTax62	-0.868***	0.0319
D1998	0.101	0.0128
D1999	0.0445	0.0129
D2000	0.147	0.0115

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Variables and statistics	Coef.	Robust standard error
D2001	0.144	0.0122
D2002	0.0656	0.00897
D2003	0.0386	0.0113
D2004	-0.014	0.0131
Constant	-0.0115	0.00956
Sample	164,570 firms	
Observations	649,809	
Min. periods	1	
Avg. periods	3.9	
Max. periods	8	
R^2 within	0.0160	
R^2 between	0.0073	
R^2 overall	0.0048	

*Note: All variables are in first differences apart from the constant, and variables with an L prefix are in log terms. *, ** and *** denote significant at the 10%, 5% and 1% level respectively. t-statistics are heteroscedasticity-robust and allow for clustering at sector level.*

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Table 6: Return on capital employed, OLS panel regression in first differences, dependent variable: ln($ROCE_{it}$)

Variables and statistics	Coef.	Robust standard error
Ltax_rate	-0.155***	0.0427
Ltax_rate-1	-0.298***	0.0486
ETS	-0.0673***	0.0185
NACExTax11	0.375***	0.026
NACExTax13	-1.37***	0.0308
NACExTax14	-0.224***	0.0673
NACExTax15	0.512***	0.0981
NACExTax16	0.766***	0.0849
NACExTax17	-0.289***	0.105
NACExTax18	-0.298**	0.112
NACExTax19	0.2	0.127
NACExTax20	-0.337**	0.136
NACExTax21	0.157***	0.0419
NACExTax22	0.342***	0.0305
NACExTax23	-0.162***	0.057
NACExTax24	-0.0174	0.0634
NACExTax25	-0.0315	0.0598
NACExTax26	-0.0686	0.13
NACExTax27	-0.0535	0.0882
NACExTax28	-0.0356	0.0843
NACExTax29	0.129*	0.0737
NACExTax30	0.416***	0.0599
NACExTax31	0.715***	0.0754
NACExTax32	0.396***	0.062
NACExTax33	0.295***	0.0598
NACExTax34	0.611***	0.0592
NACExTax35	0.404***	0.054
NACExTax36	0.98***	0.0477
NACExTax37	0.649***	0.08
NACExTax40	0.267***	0.0534
NACExTax41	0.147***	0.0534
NACExTax45	-0.000523	0.0556
NACExTax60	0.514***	0.0528
NACExTax61	0.0725	0.058
NACExTax62	1.2***	0.047

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Variablcs and statistics	Cocf.	Robust standard crror
NACExTax11	1.47***	0.0314
NACExTax13	2.29***	0.113
NACExTax14	0.412***	0.111
NACExTax15	-0.362***	0.0748
NACExTax16	0.884***	0.0519
NACExTax17	0.995***	0.2
NACExTax18	1.14***	0.204
NACExTax19	0.801***	0.166
NACExTax20	0.23	0.147
NACExTax21	-0.106	0.0825
NACExTax22	0.144***	0.0505
NACExTax23	-0.0366	0.0271
NACExTax24	0.518***	0.0446
NACExTax25	0.569***	0.0483
NACExTax26	1.41***	0.229
NACExTax27	0.637***	0.0758
NACExTax28	0.605***	0.0785
NACExTax29	0.6***	0.106
NACExTax30	1.1***	0.0695
NACExTax31	0.523***	0.0703
NACExTax32	0.533***	0.0662
NACExTax33	0.66***	0.0672
NACExTax34	0.619***	0.0923
NACExTax35	0.352***	0.0872
NACExTax36	0.577***	0.0775
NACExTax37	-0.135***	0.0415
NACExTax40	0.171***	0.0354
NACExTax41	0.299***	0.0474
NACExTax45	0.611***	0.0894
NACExTax60	-0.000539	0.0508
NACExTax61	-0.542***	0.0525
NACExTax62	1.02***	0.0528
D1999	-0.404***	0.0918
D2000	-0.21***	0.0505
D2001	-0.213***	0.0296
D2002	-0.251***	0.0355

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Variables and statistics	Coef.	Robust standard error
D2003	-0.292***	0.0411
D2004	-0.23***	0.0463
D2005	-0.236***	0.0465
Constant	0.15***	0.0432
Sample	162,771 firms	
Observations	506,682	
Min. periods	1	
Avg. periods	3.1	
Max. periods	8	
R^2 within	0.0082	
R^2 between	0.0027	
R^2 overall	0.0064	

*Note: All variables are in first differences apart from the constant, and variables with an L prefix are in log terms. *, ** and *** denote significant at the 10%, 5% and 1% level respectively. t-statistics are heteroscedasticity-robust and allow for clustering at sector level.*

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Table 7: Investment, OLS panel regression in first differences, dependent variable: ln(investment$_{it}$)

Variables and statistics	Coef.	Robust standard error
Ltax_rate	-1.68***	0.0303
Ltax_rate-1	1.92***	0.0554
ETS	0.00161	0.0249
NACExTax11	1.93***	0.0257
NACExTax13	-0.225***	0.0469
NACExTax14	1.65***	0.0535
NACExTax15	1.73***	0.0296
NACExTax16	1.45***	0.0498
NACExTax17	1.68***	0.103
NACExTax18	1.13***	0.115
NACExTax19	1.27***	0.0325
NACExTax20	1.9***	0.0954
NACExTax21	1.67***	0.0385
NACExTax22	1.73***	0.0305
NACExTax23	2.37***	0.0364
NACExTax24	1.93***	0.048
NACExTax25	1.38***	0.0404
NACExTax26	0.847***	0.129
NACExTax27	2.43***	0.0586
NACExTax28	1.87***	0.0544
NACExTax29	1.85***	0.0622
NACExTax30	1.31***	0.0383
NACExTax31	1.49***	0.0376
NACExTax32	1.14***	0.0398
NACExTax33	1.31***	0.041
NACExTax34	2***	0.0346
NACExTax35	1.94***	0.0374
NACExTax36	1.49***	0.0911
NACExTax37	0.307***	0.0725
NACExTax40	1.95***	0.0301
NACExTax41	1.75***	0.0311
NACExTax45	1.26***	0.0627
NACExTax60	1.45***	0.0493
NACExTax61	1.41***	0.0498
NACExTax62	2.62***	0.0446

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Variablcs and statistics	Cocf.	Robust standard crror
NACExTax11	-1.78***	0.039
NACExTax13	-0.141***	0.0462
NACExTax14	-1.73***	0.0353
NACExTax15	-2.05***	0.037
NACExTax16	-5.31***	0.0466
NACExTax17	-1.93***	0.105
NACExTax18	-1.69***	0.105
NACExTax19	-2.63***	0.0615
NACExTax20	-1.93***	0.0713
NACExTax21	-1.68***	0.044
NACExTax22	-1.94***	0.0431
NACExTax23	-1.85***	0.0669
NACExTax24	-1.97***	0.0595
NACExTax25	-1.96***	0.0615
NACExTax26	-1.65***	0.0461
NACExTax27	-1.78***	0.065
NACExTax28	-1.88***	0.0622
NACExTax29	-1.73***	0.0165
NACExTax30	-1.34***	0.0467
NACExTax31	-1.8***	0.0457
NACExTax32	-1.81***	0.0481
NACExTax33	-1.61***	0.0498
NACExTax34	-2.11***	0.0368
NACExTax35	-1.77***	0.037
NACExTax36	-1.85***	0.0966
NACExTax37	-2.18***	0.0861
NACExTax40	-1.88***	0.0554
NACExTax41	-1.96***	0.0556
NACExTax45	-2.03***	0.0796
NACExTax60	-1.52***	0.0488
NACExTax61	-0.877***	0.0507
NACExTax62	-0.802***	0.0533
D1999	-0.0204	0.0395
D2000	-0.0842**	0.0412
D2001	-0.196***	0.0368
D2002	-0.113**	0.0468

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Variables and statistics	Coef.	Robust standard error
D2003	-0.151***	0.0354
D2004	-0.074*	0.037
D2005	-0.148***	0.0367
Constant	0.166***	0.0371
Sample	138,776 firms	
Observations	427,483	
Min. periods	1	
Avg. periods	3.1	
Max. periods	8	
R^2 within	0.0017	
R^2 between	0.0002	
R^2 overall	0.0012	

*Note: All variables are in first differences apart from the constant, and variables with an L prefix are in log terms. *, ** and *** denote significant at the 10%, 5% and 1% level respectively. t-statistics are heteroscedasticity-robust and allow for clustering at sector level.*

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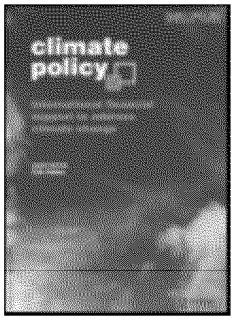

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

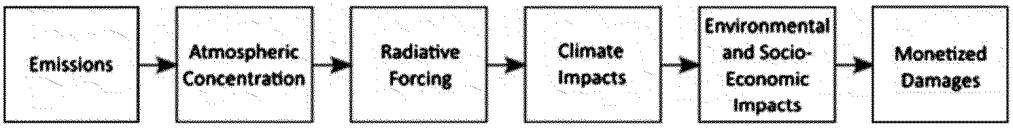

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4}\ - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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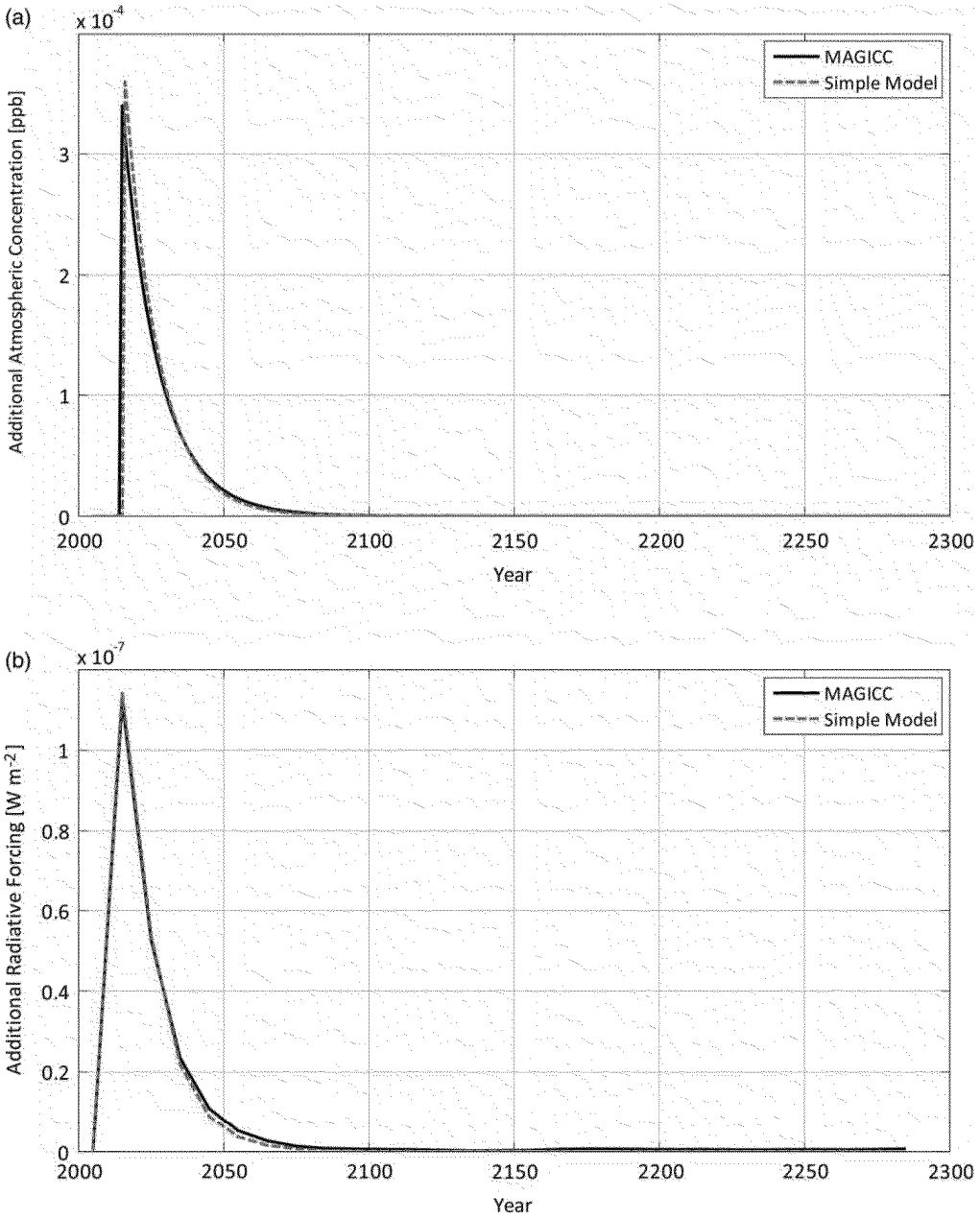

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})], \right. \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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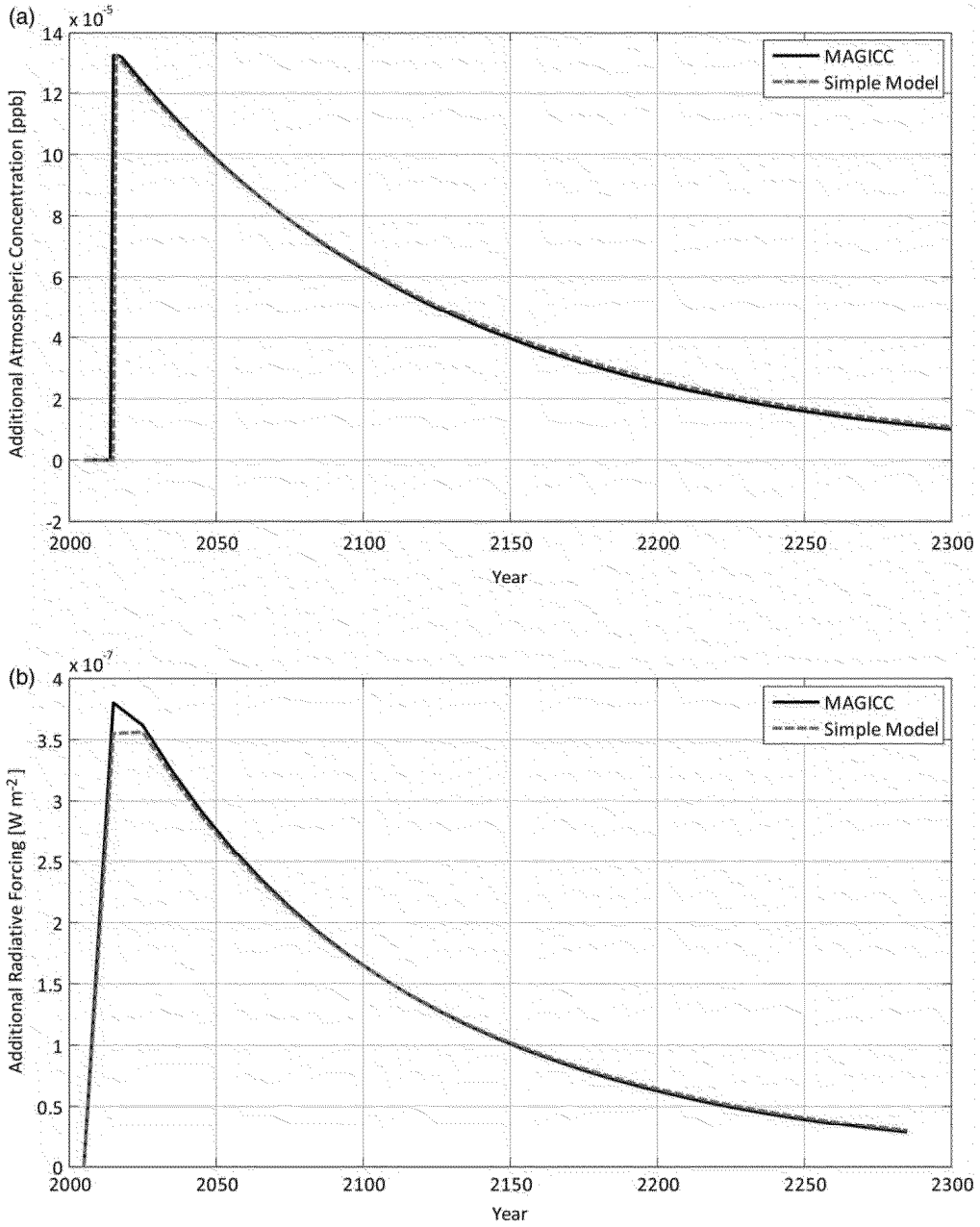

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

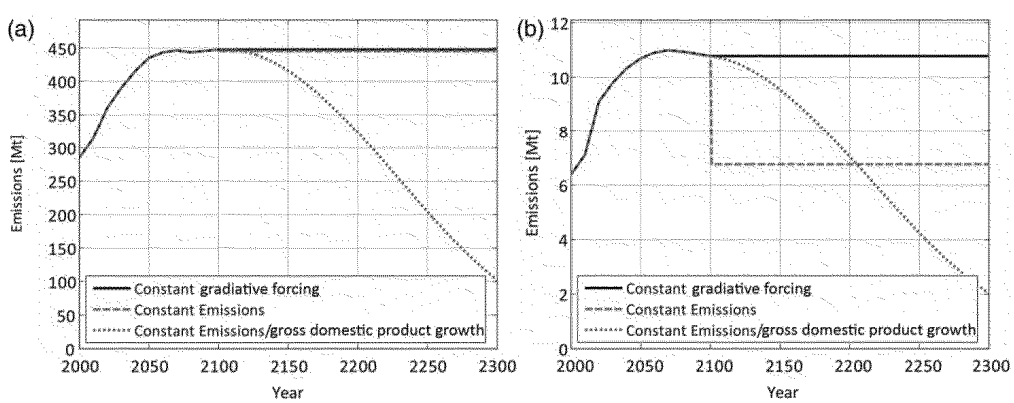

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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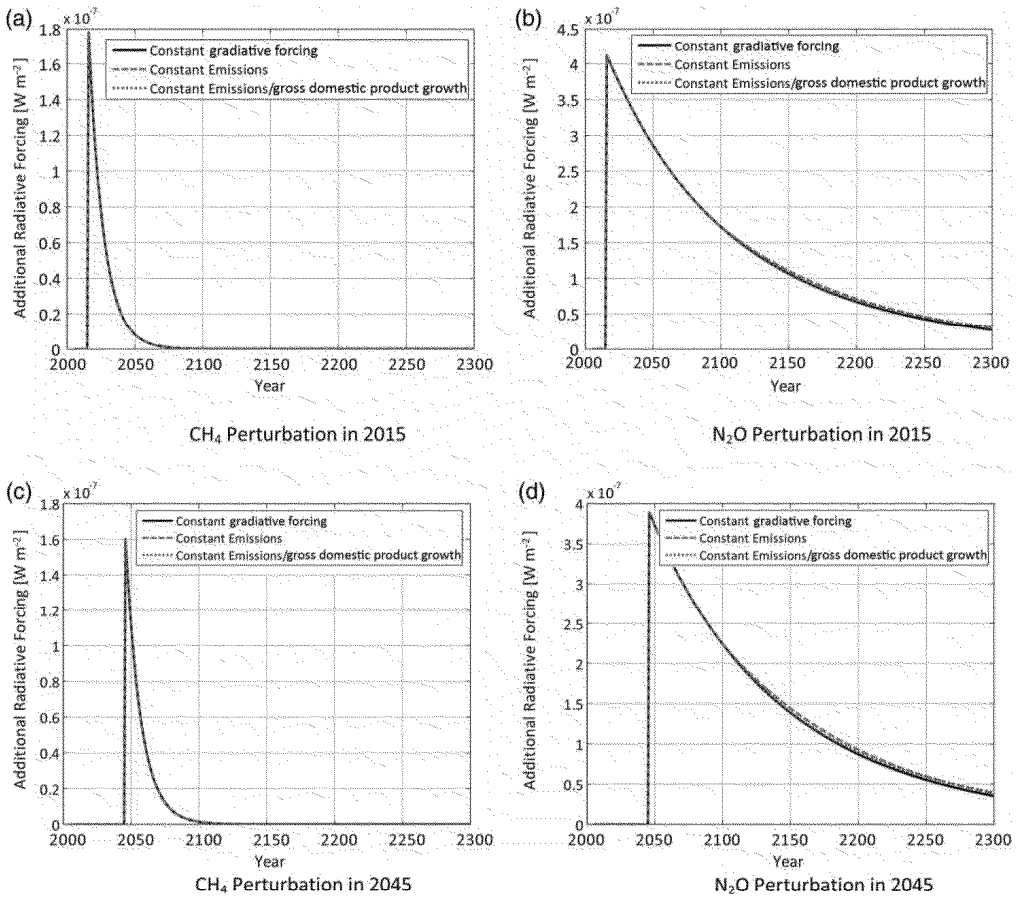

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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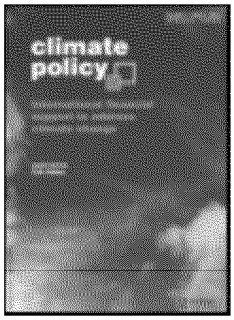

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

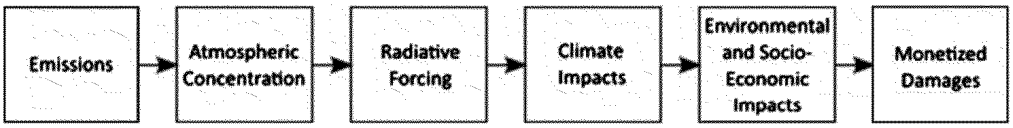

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4}\ - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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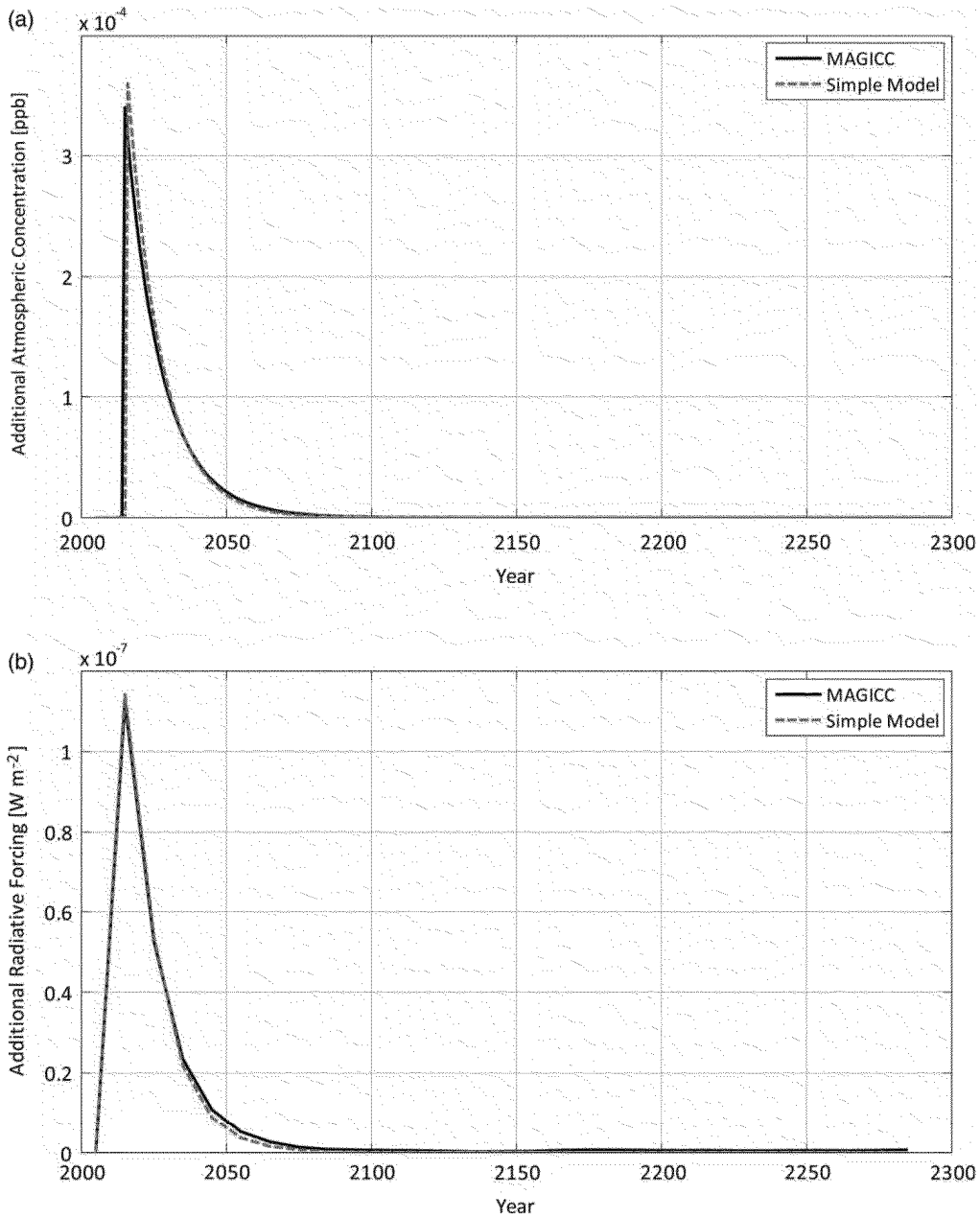

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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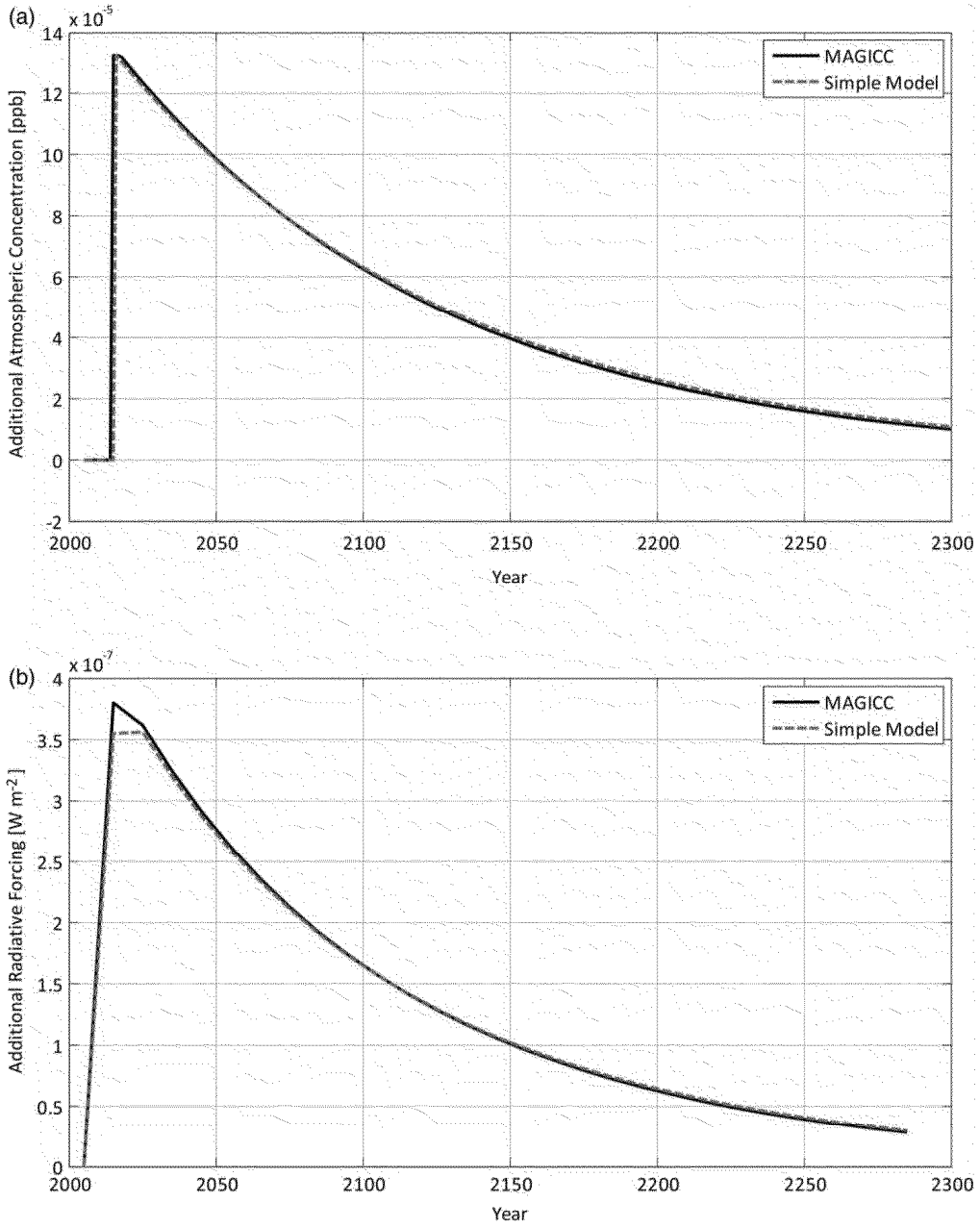

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

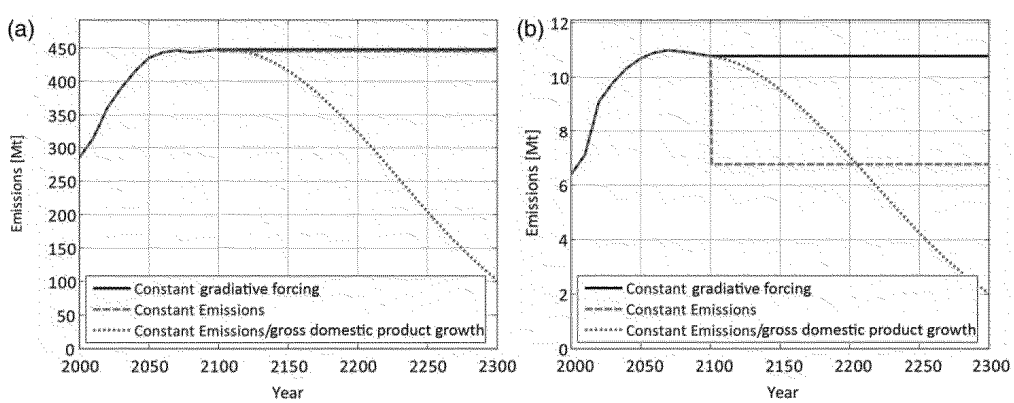

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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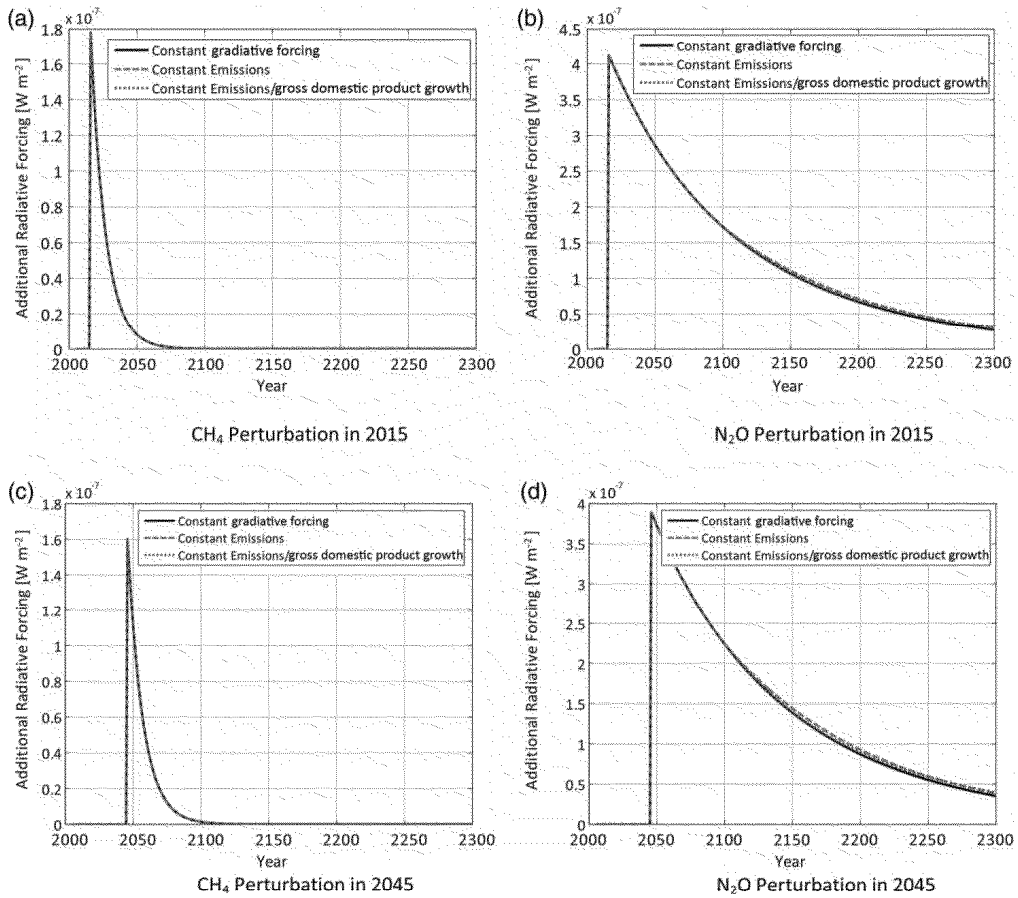

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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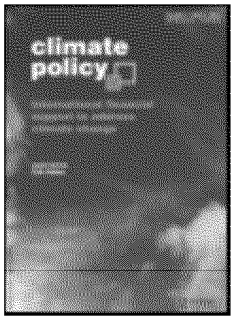

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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†The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the US Environmental Protection Agency.

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

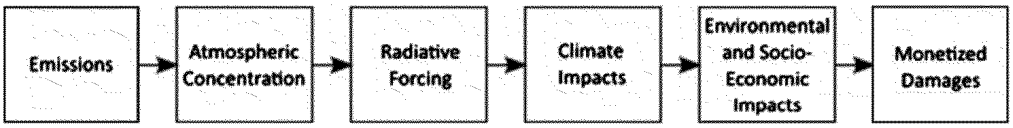

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4}\ - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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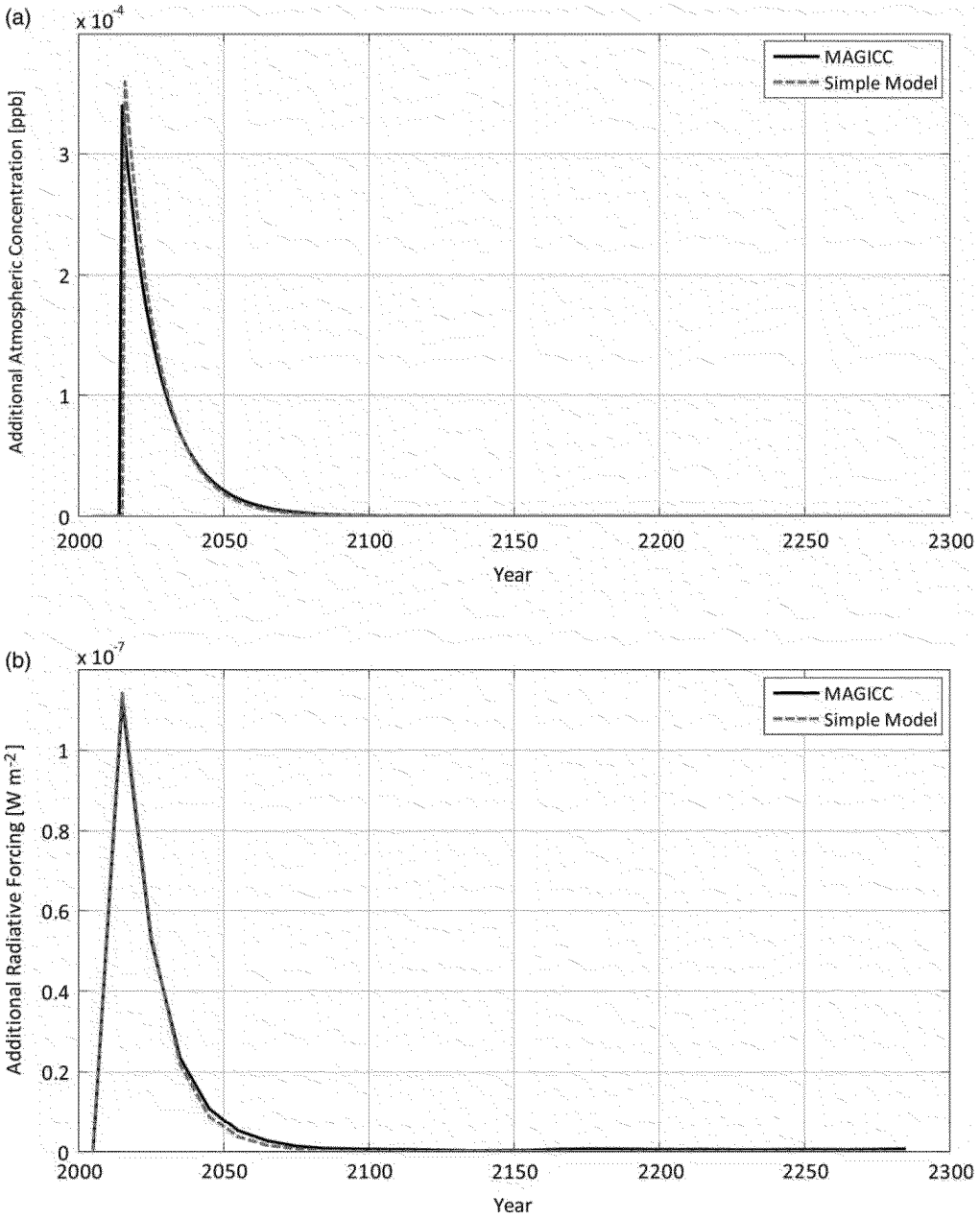

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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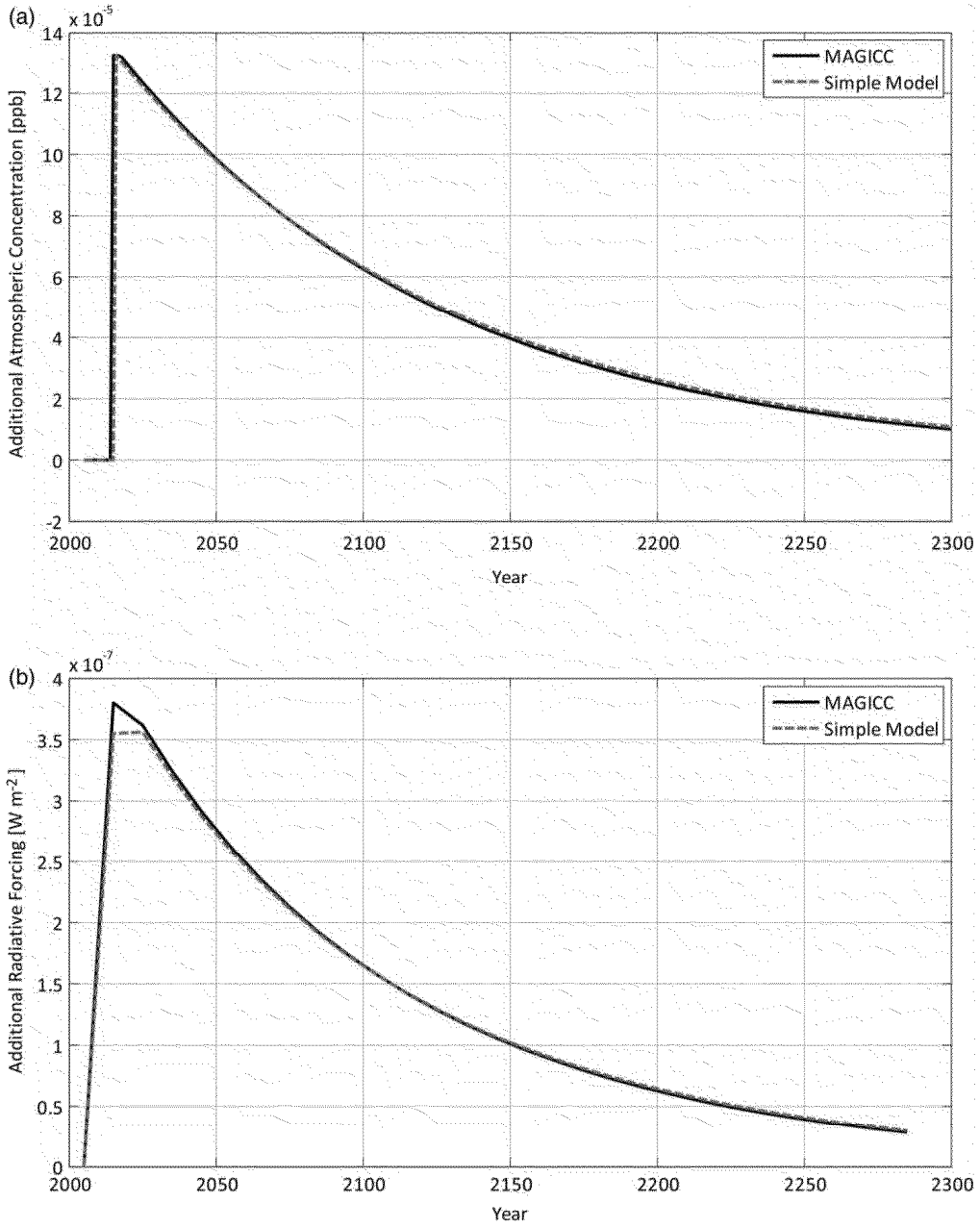

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

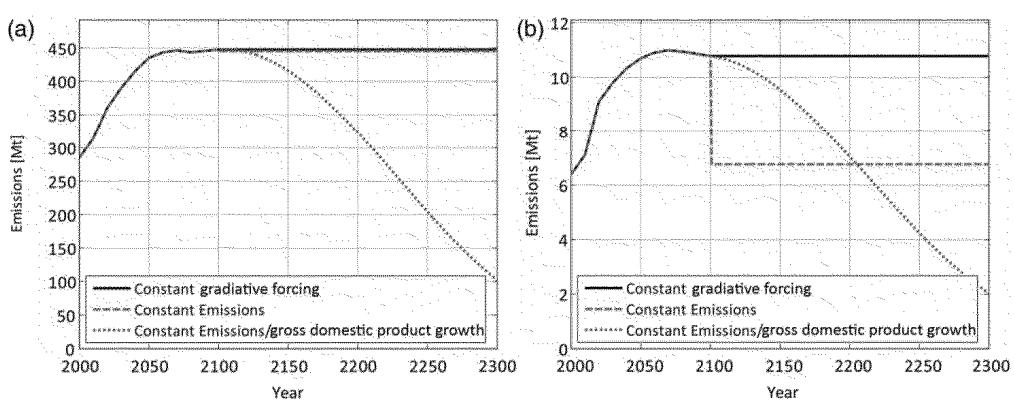

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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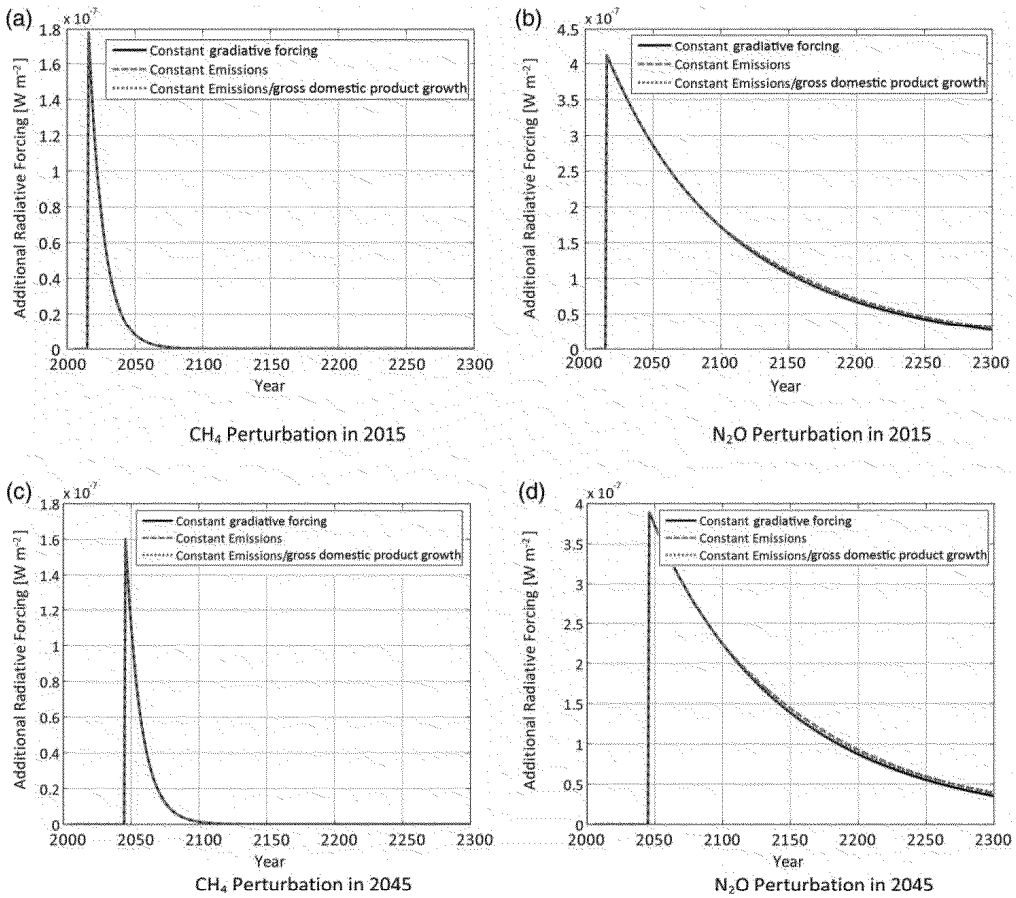

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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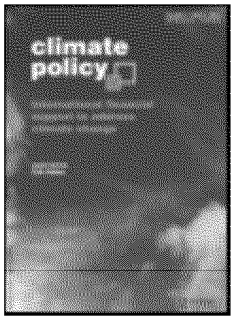

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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†The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the US Environmental Protection Agency.

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

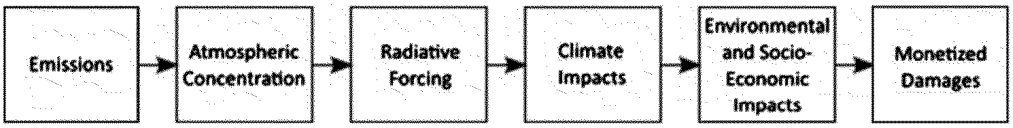

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4}\ - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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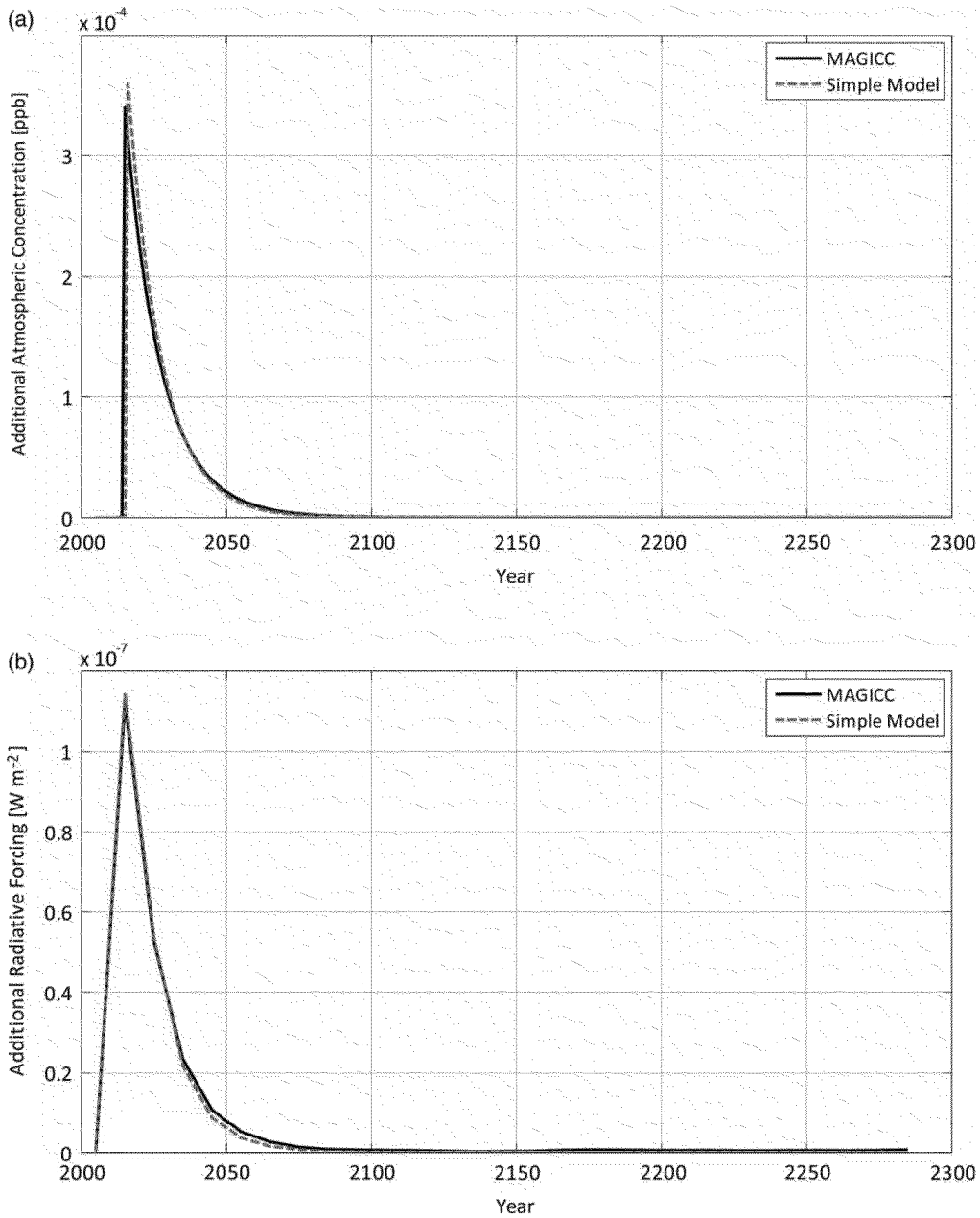

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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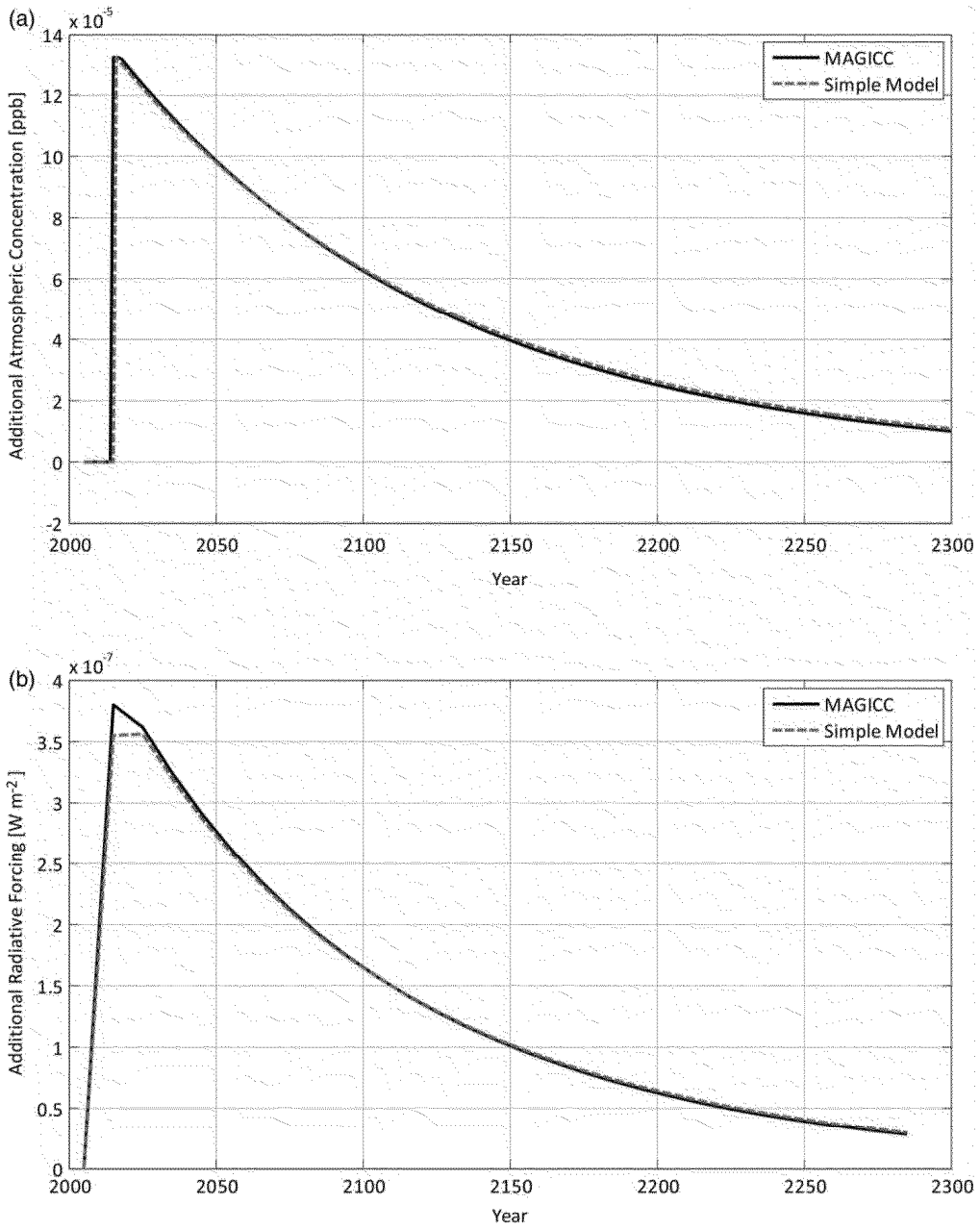

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

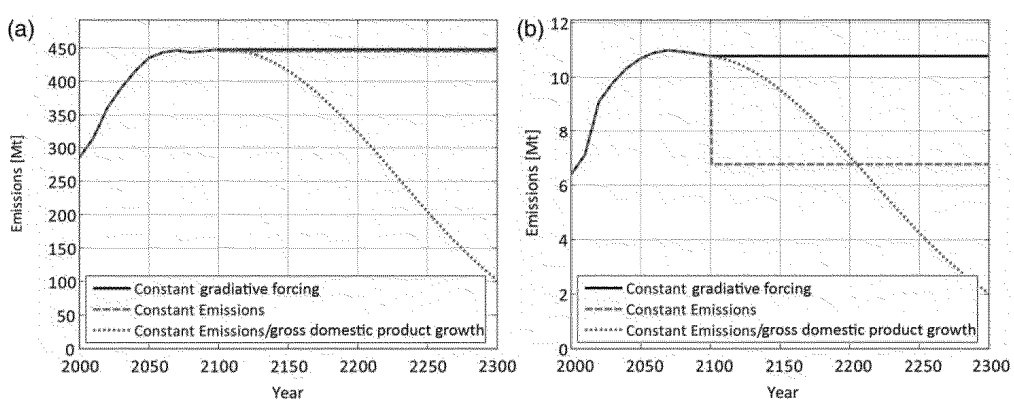

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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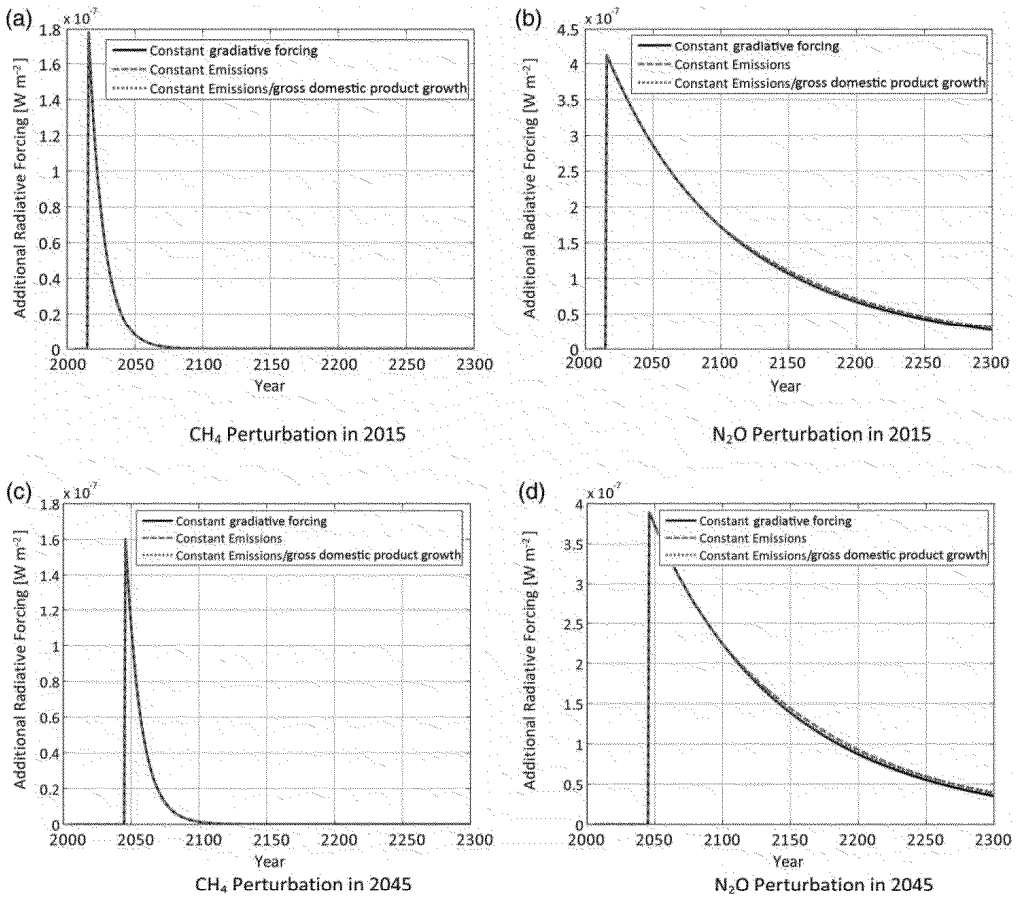

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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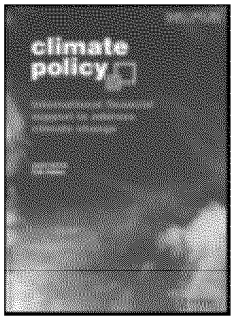

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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†The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the US Environmental Protection Agency.

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

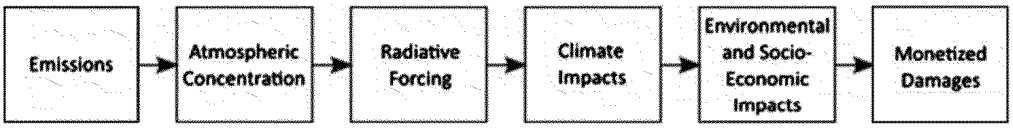

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4}\ - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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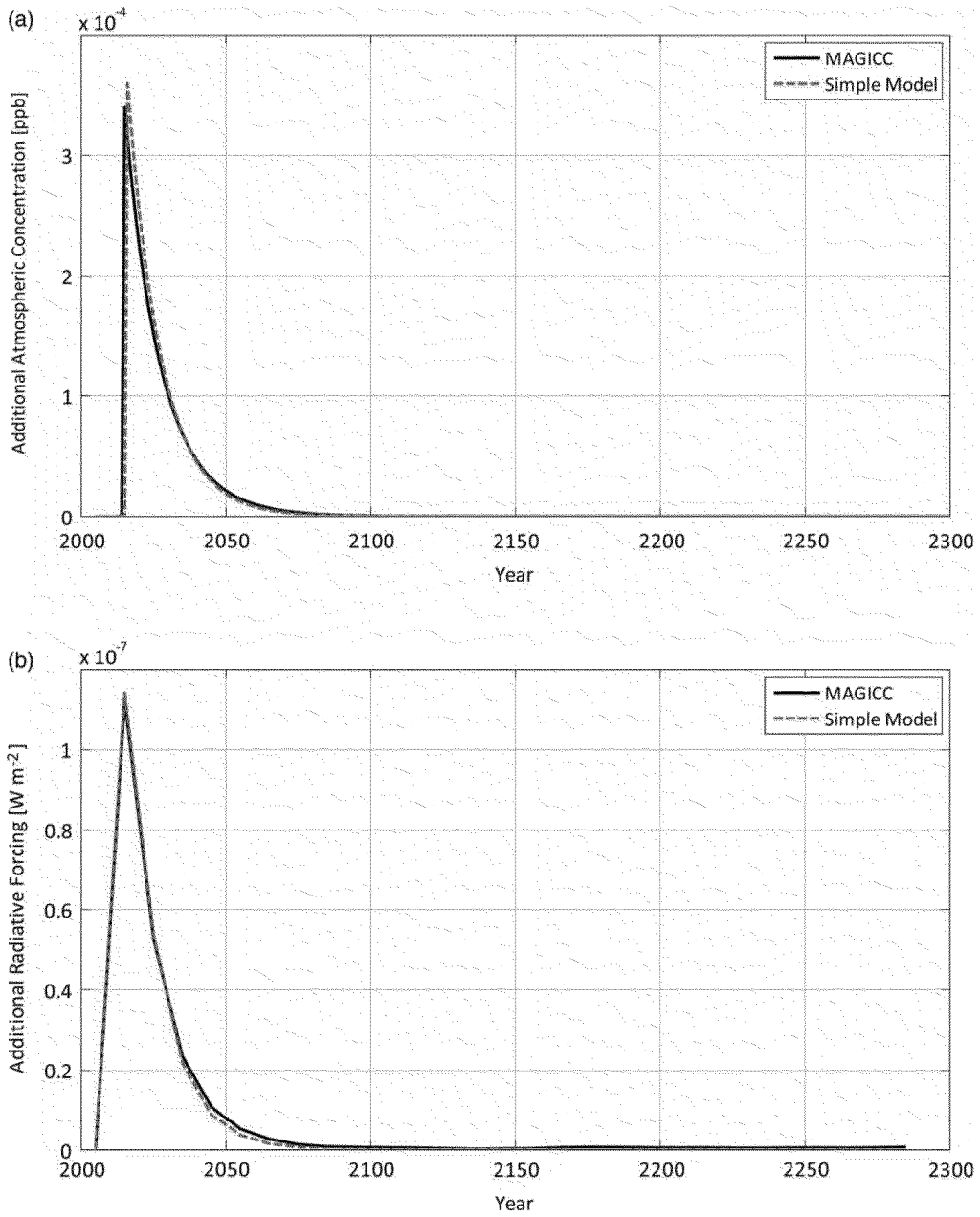

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})], \right. \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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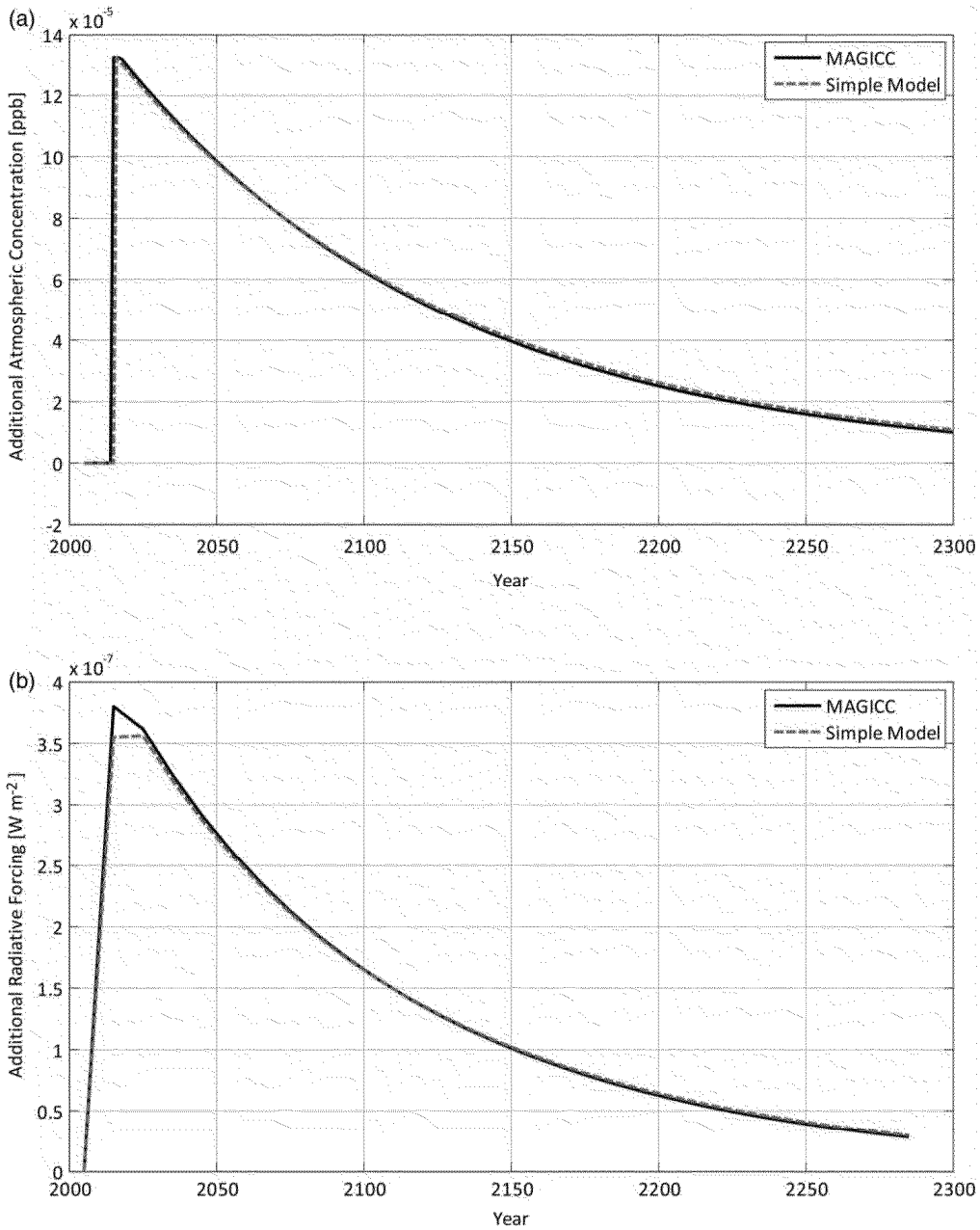

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

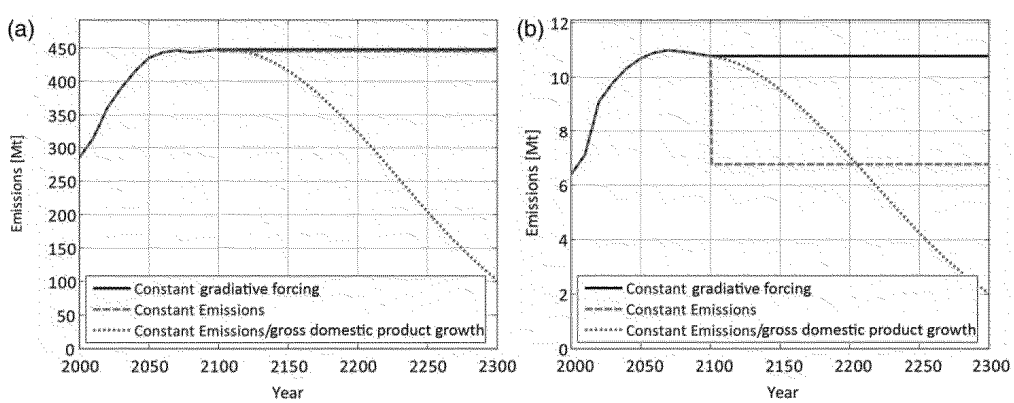

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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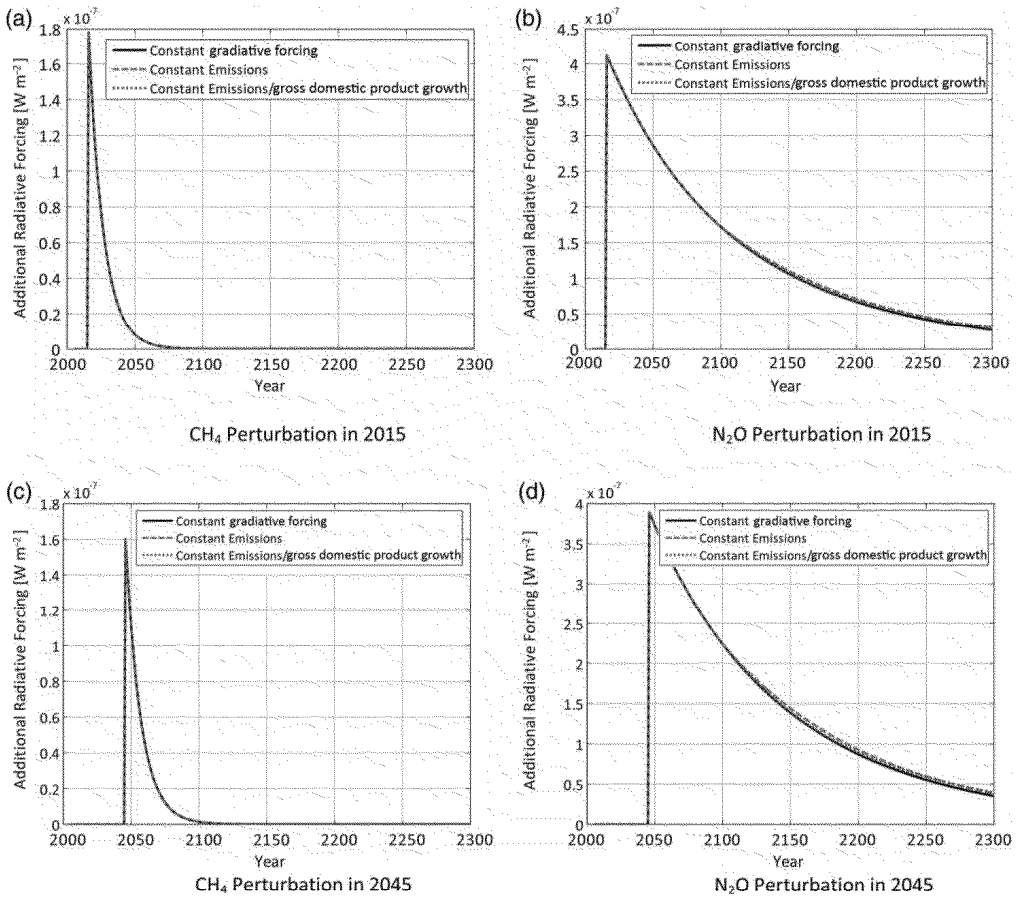

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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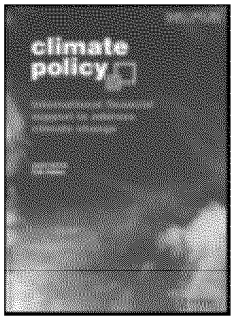

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

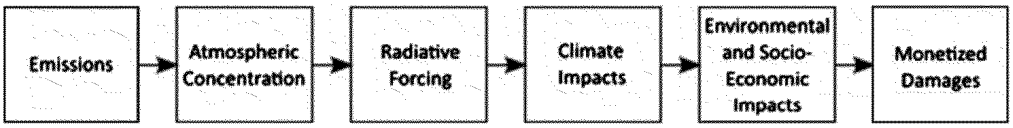

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \left(C_t^{CH_4} - C_{pre}^{CH_4}\right) - \left[f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})\right], \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln\left[1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})\right]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}. \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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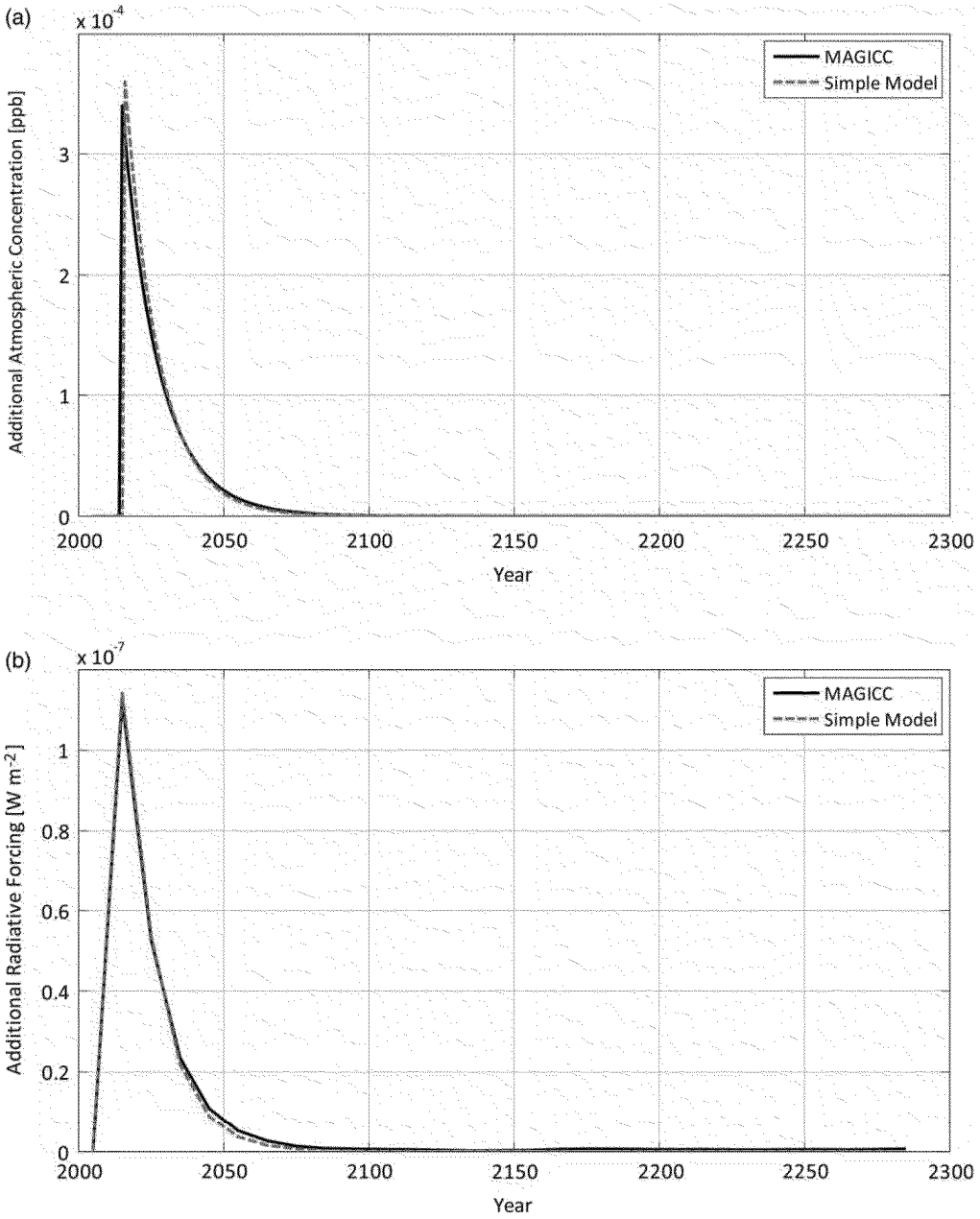

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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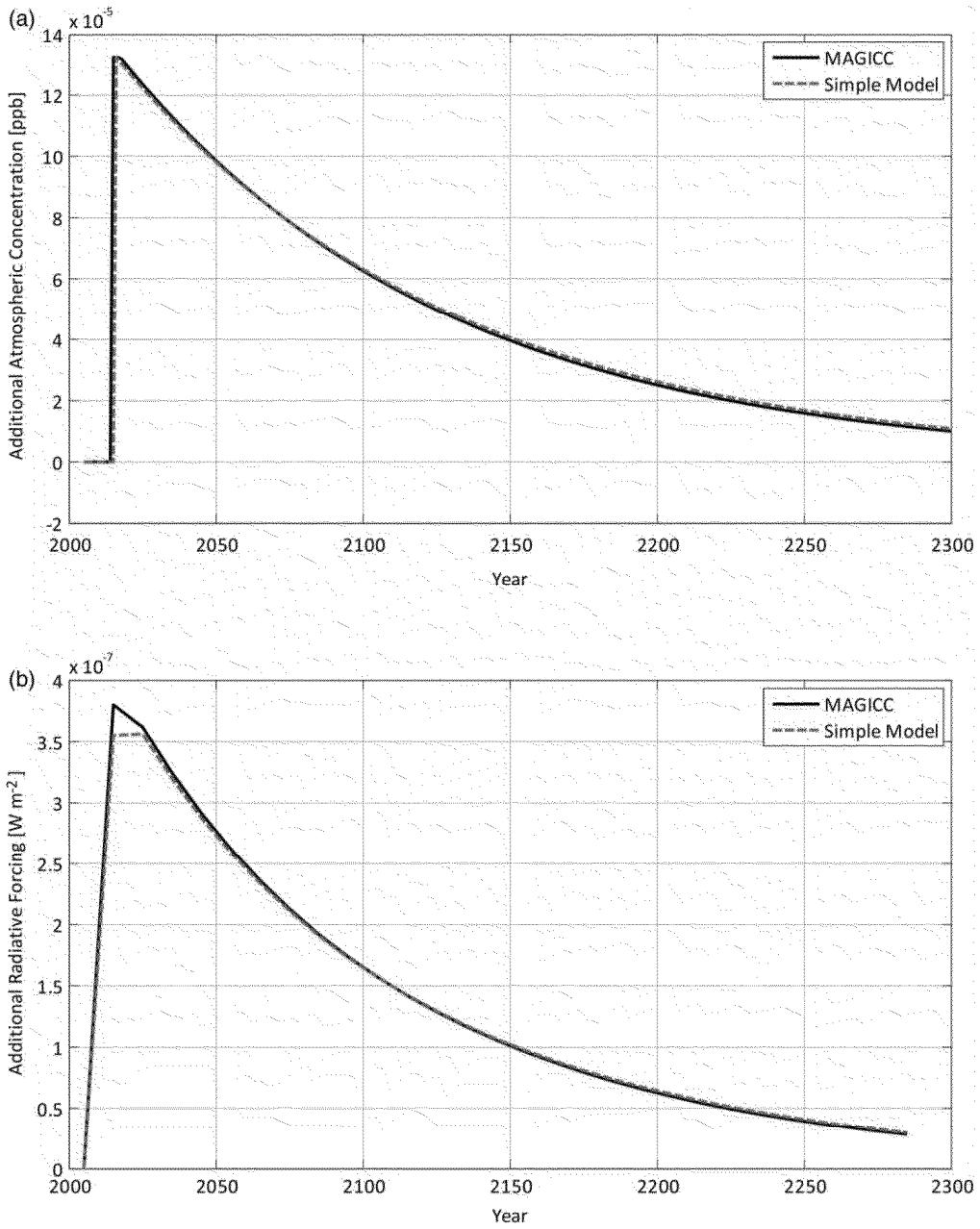

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

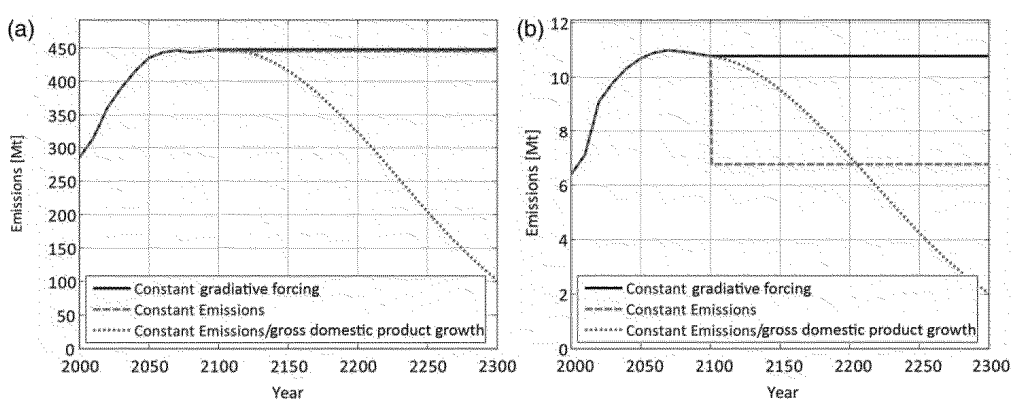

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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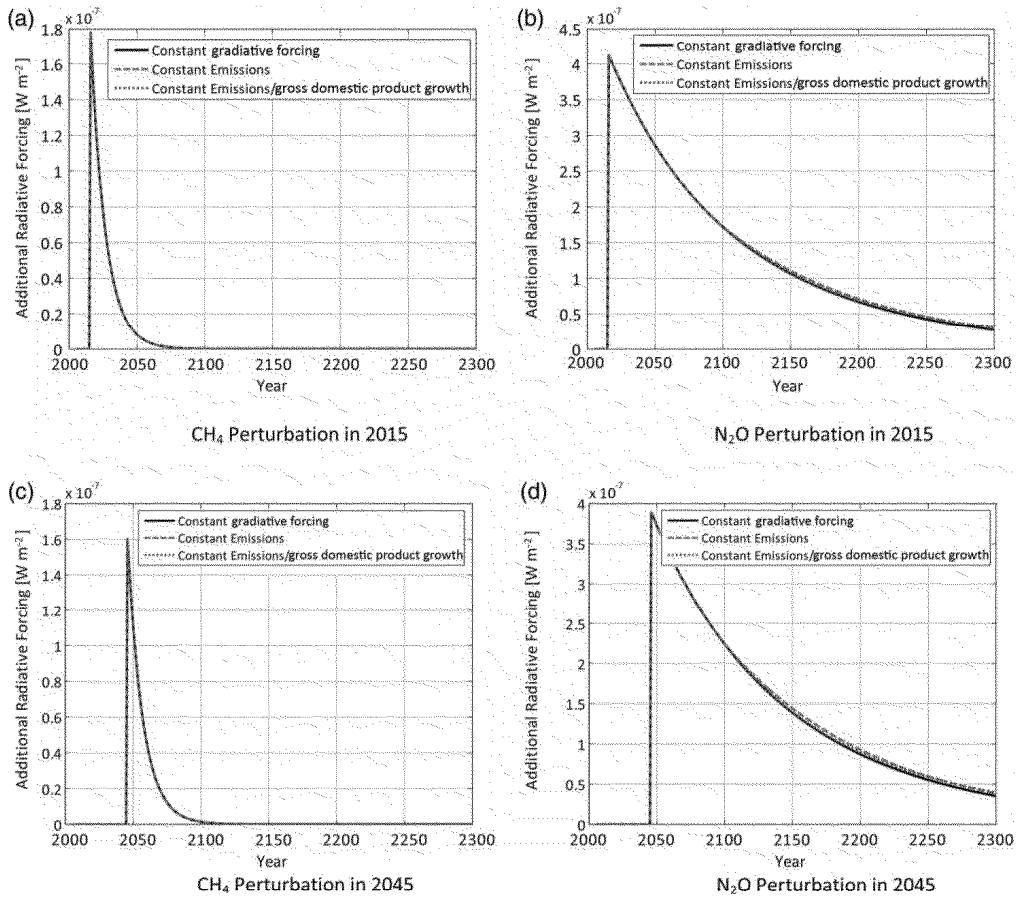

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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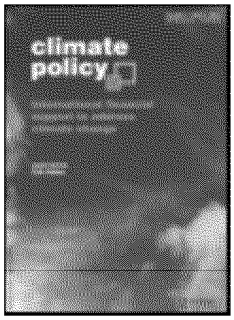

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

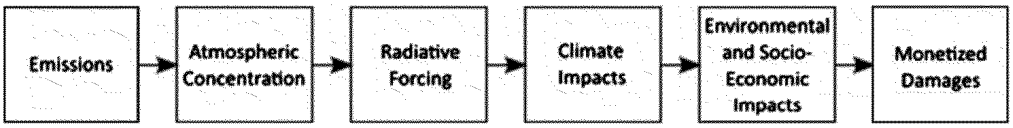

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4}\ - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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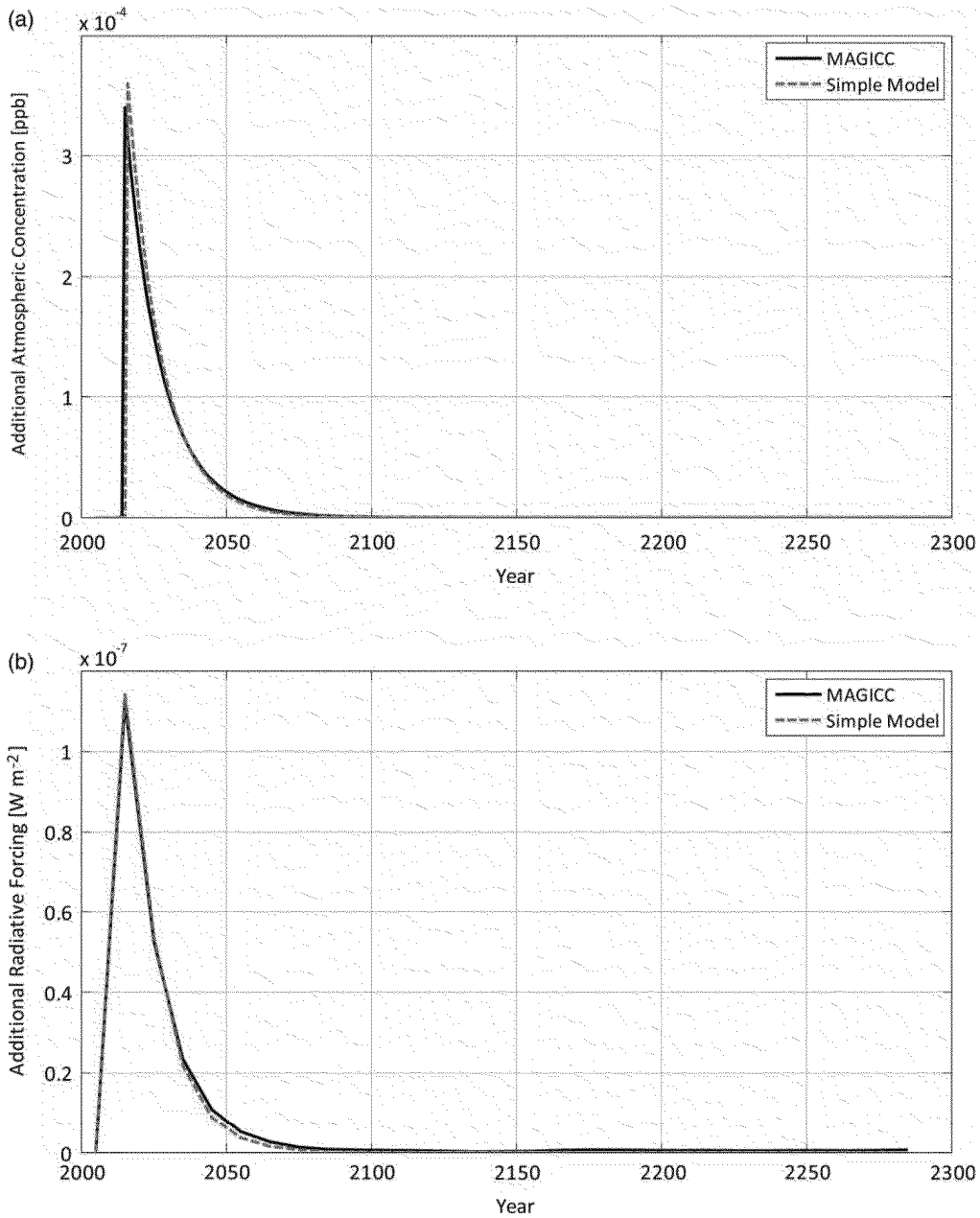

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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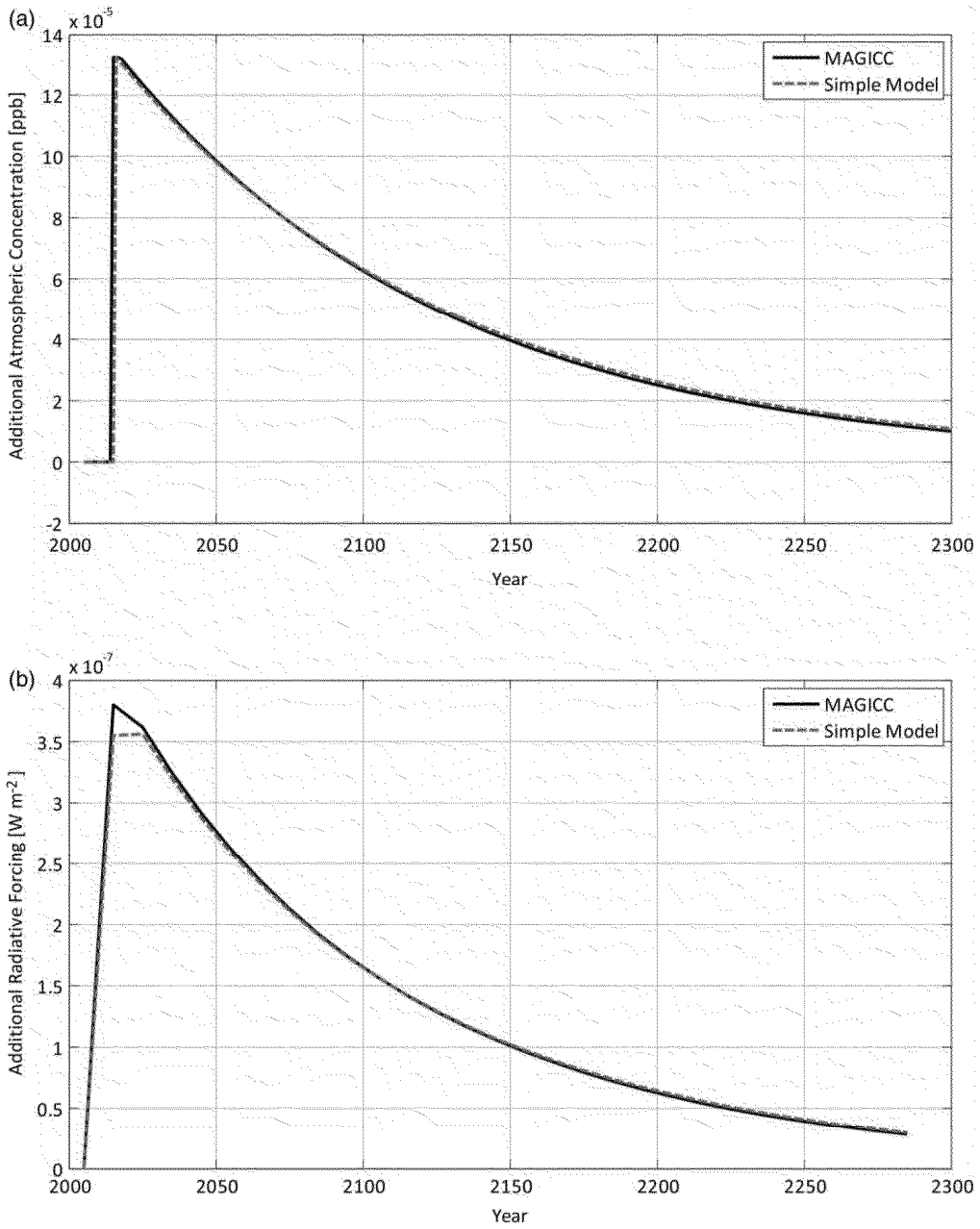

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

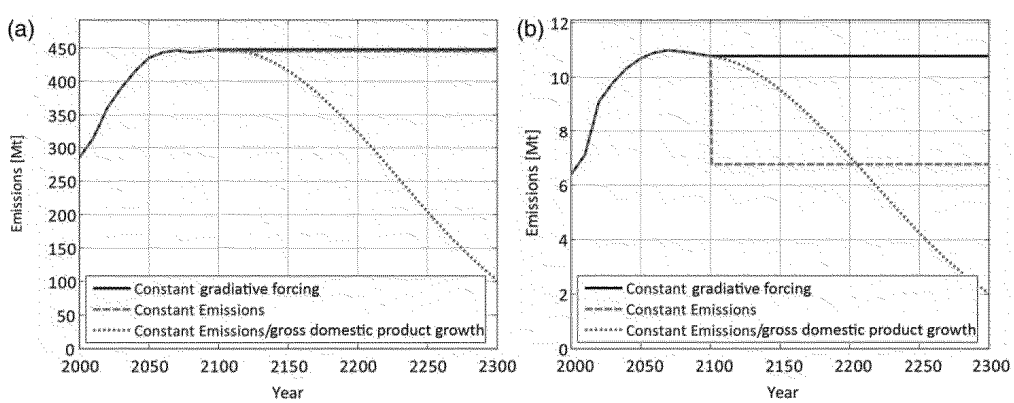

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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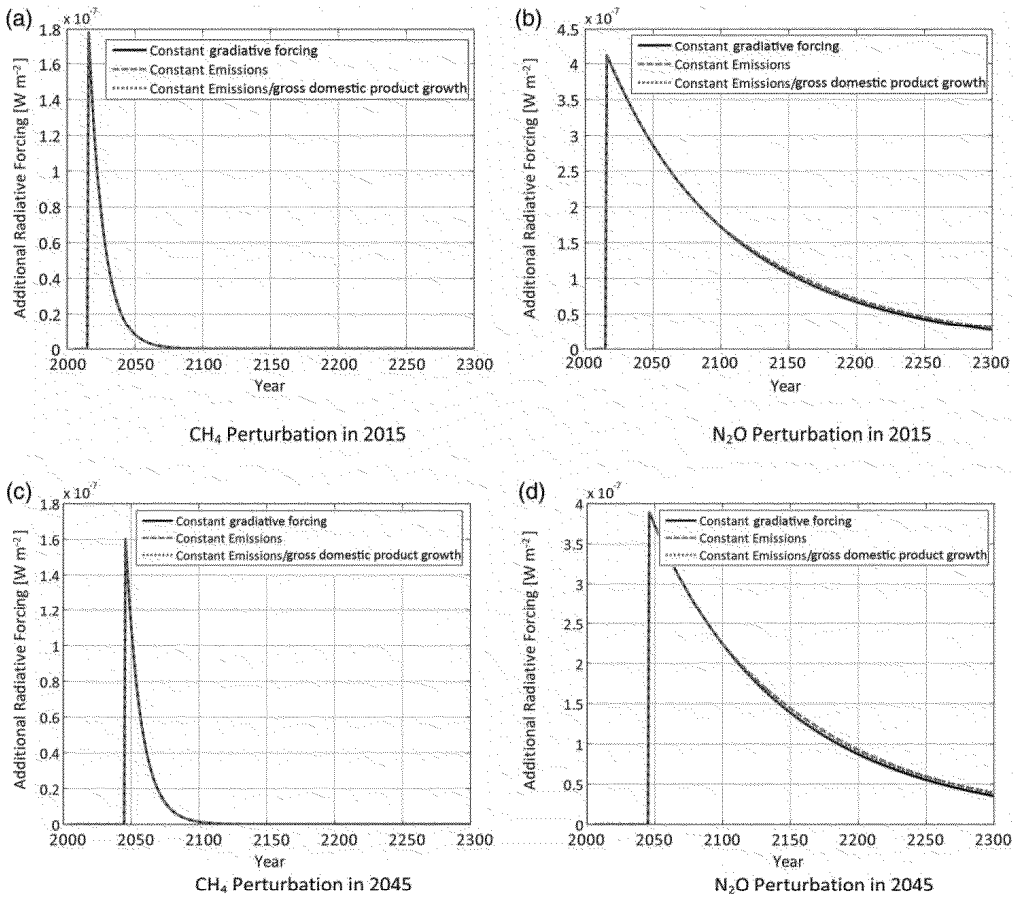

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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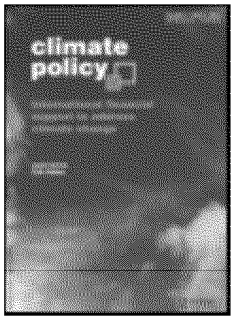

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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†The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the US Environmental Protection Agency.

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

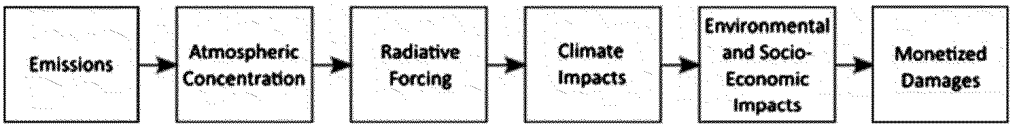

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \left(C_t^{CH_4} - C_{pre}^{CH_4}\right) - \left[f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})\right], \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln\left[1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})\right]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}. \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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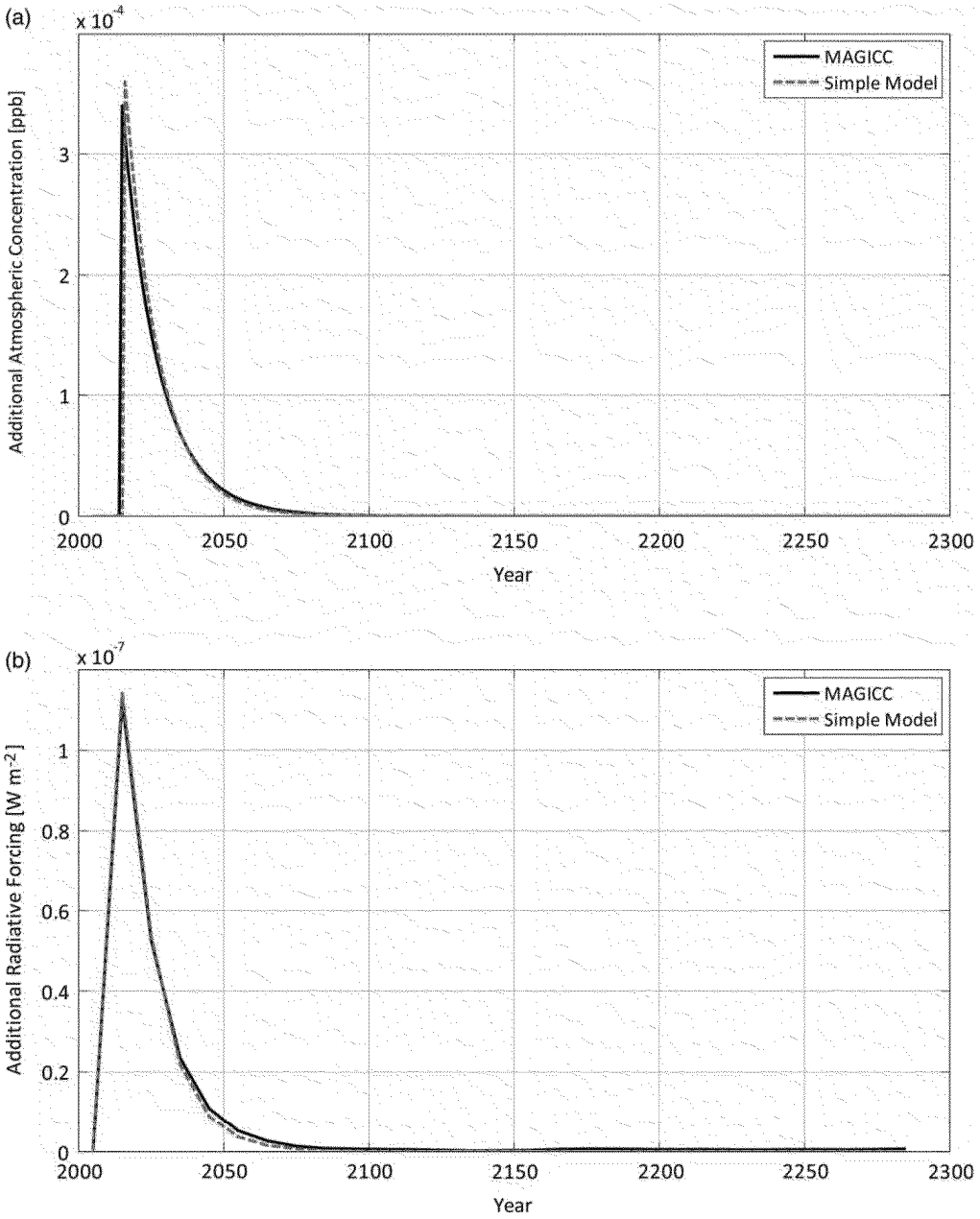

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})], \right. \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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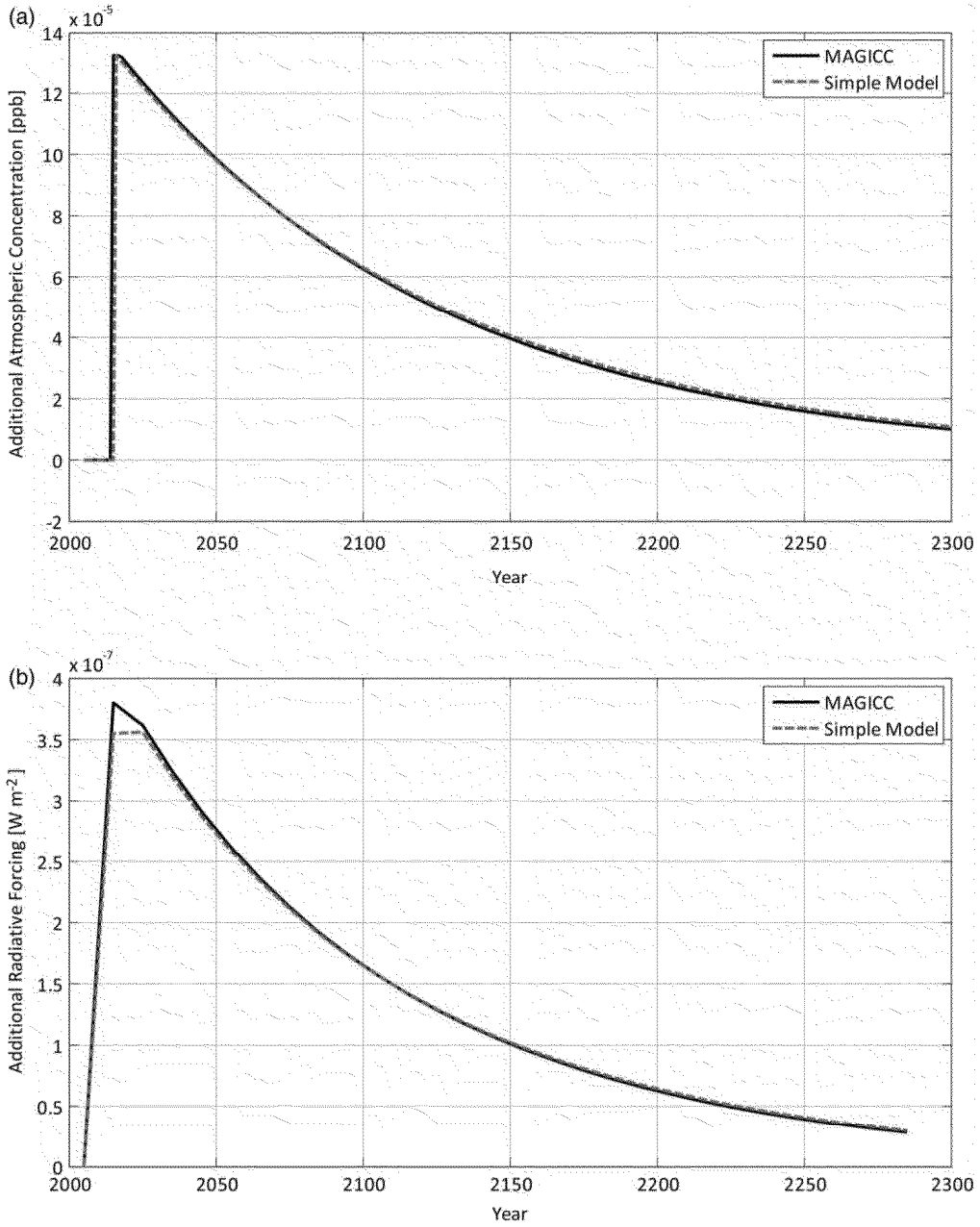

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

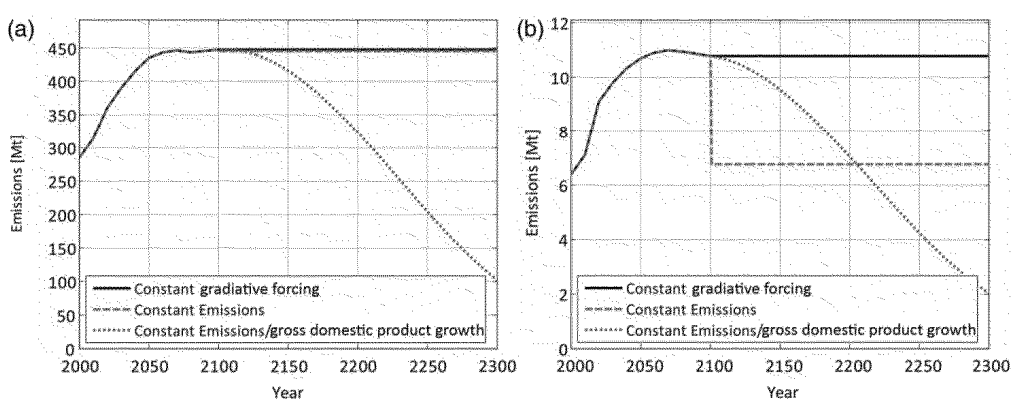

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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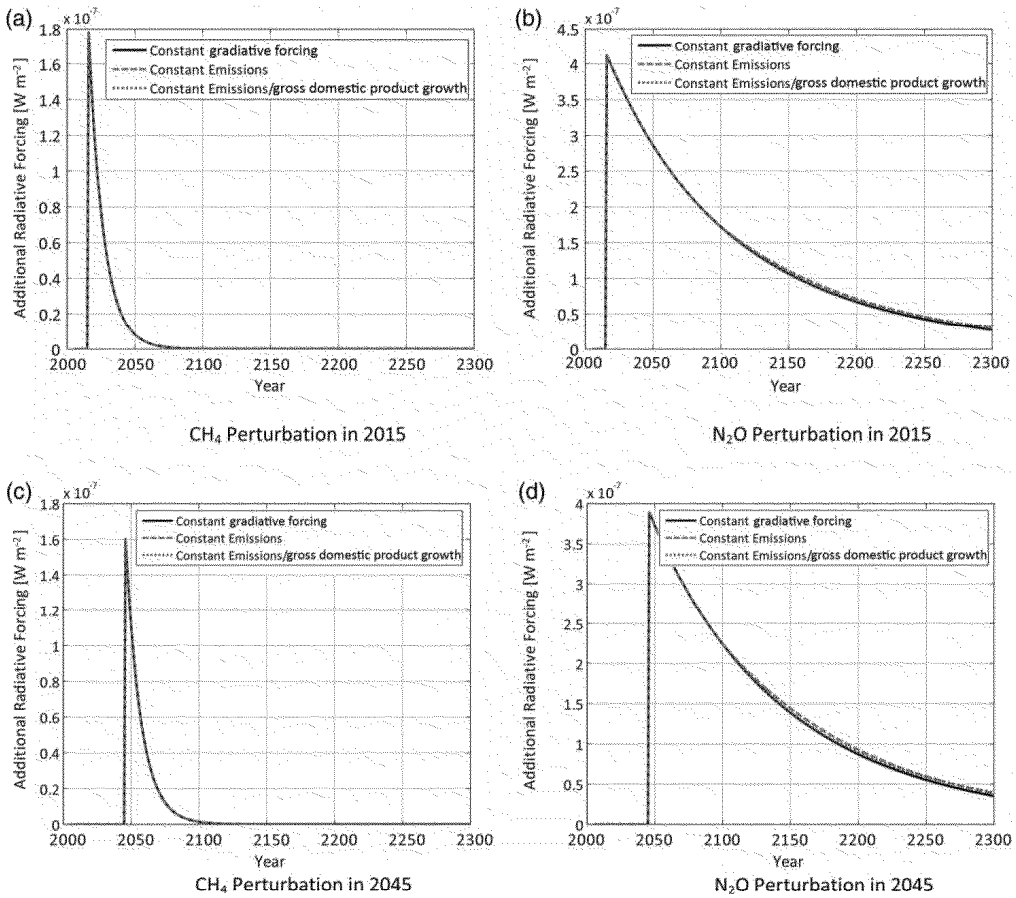

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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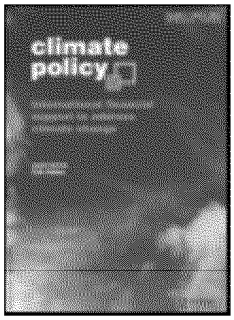

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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climate policy

B research article

Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

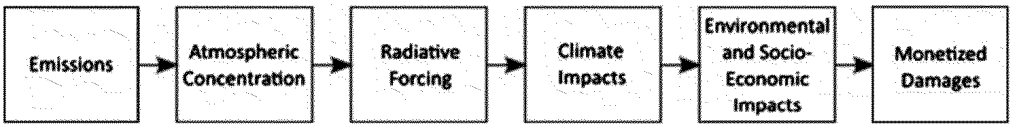

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \ C_t^{CH_4} - \ C_{pre}^{CH_4}\ - [f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})]\ , \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln 1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}\ . \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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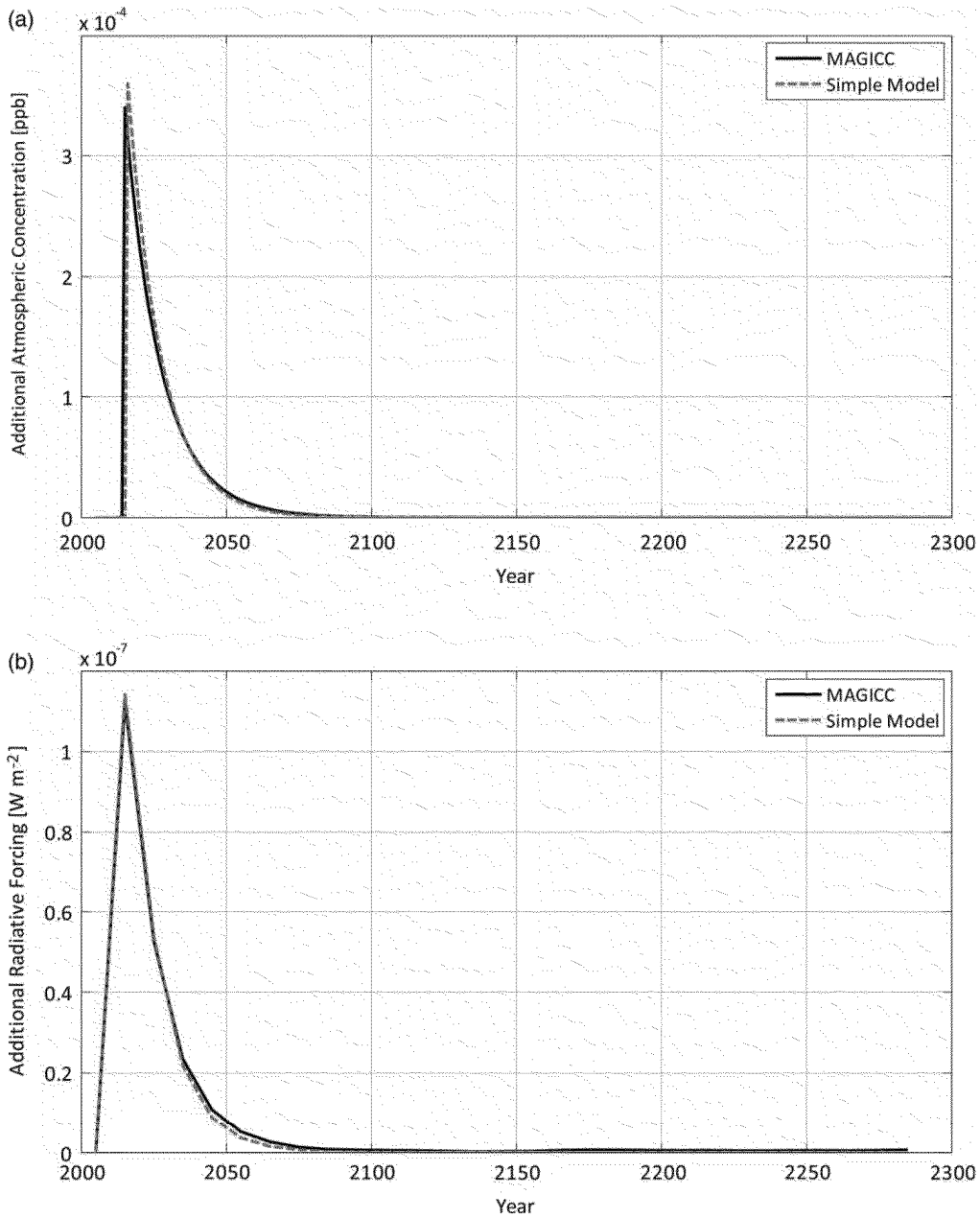

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})], \right. \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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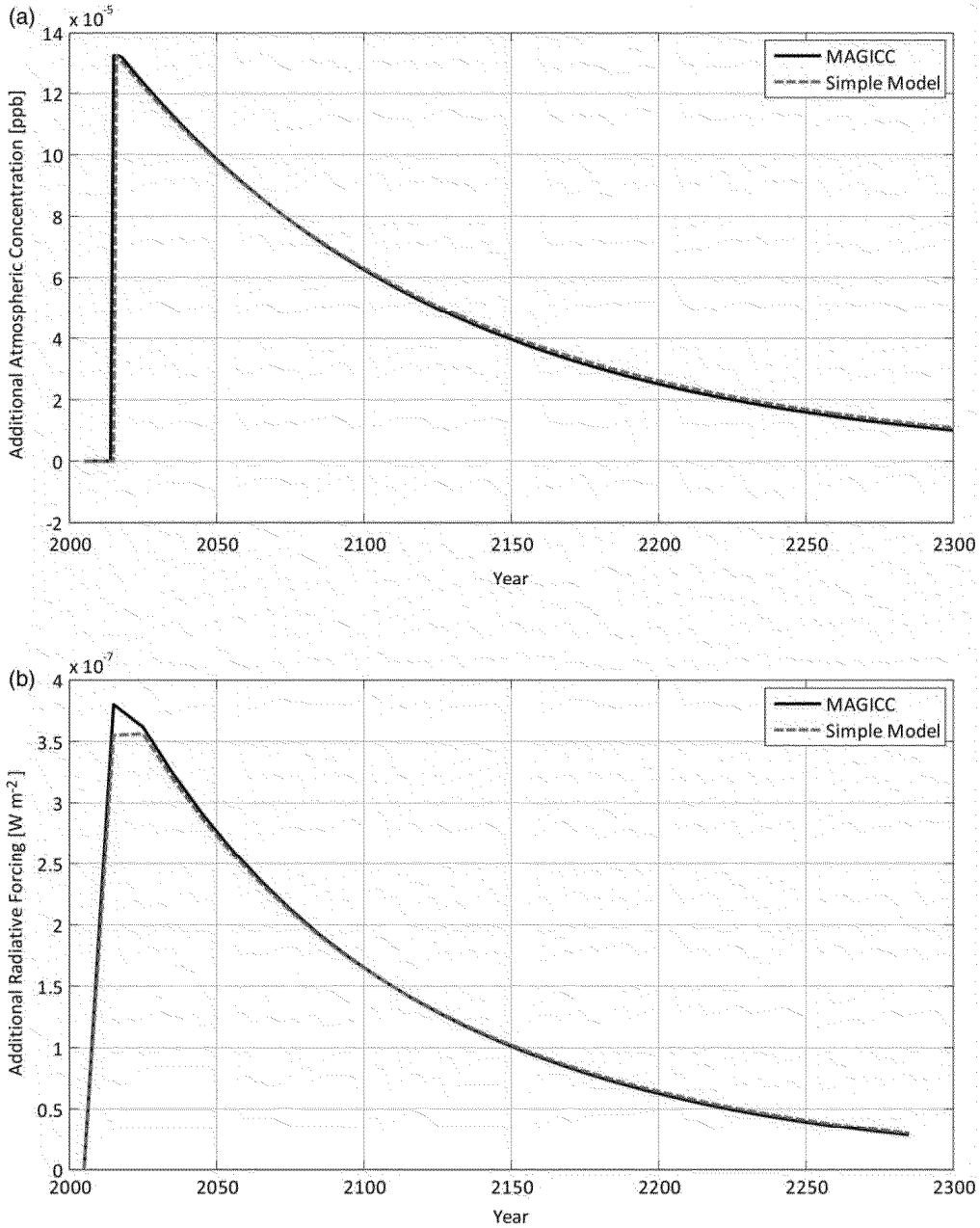

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

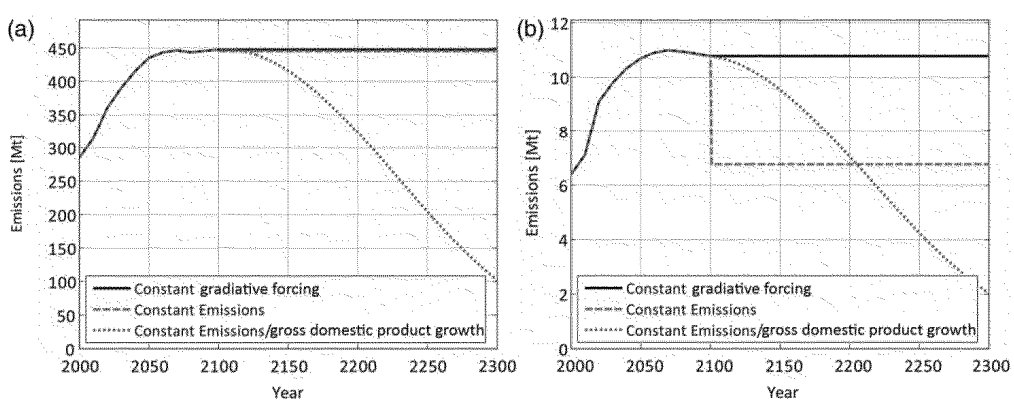

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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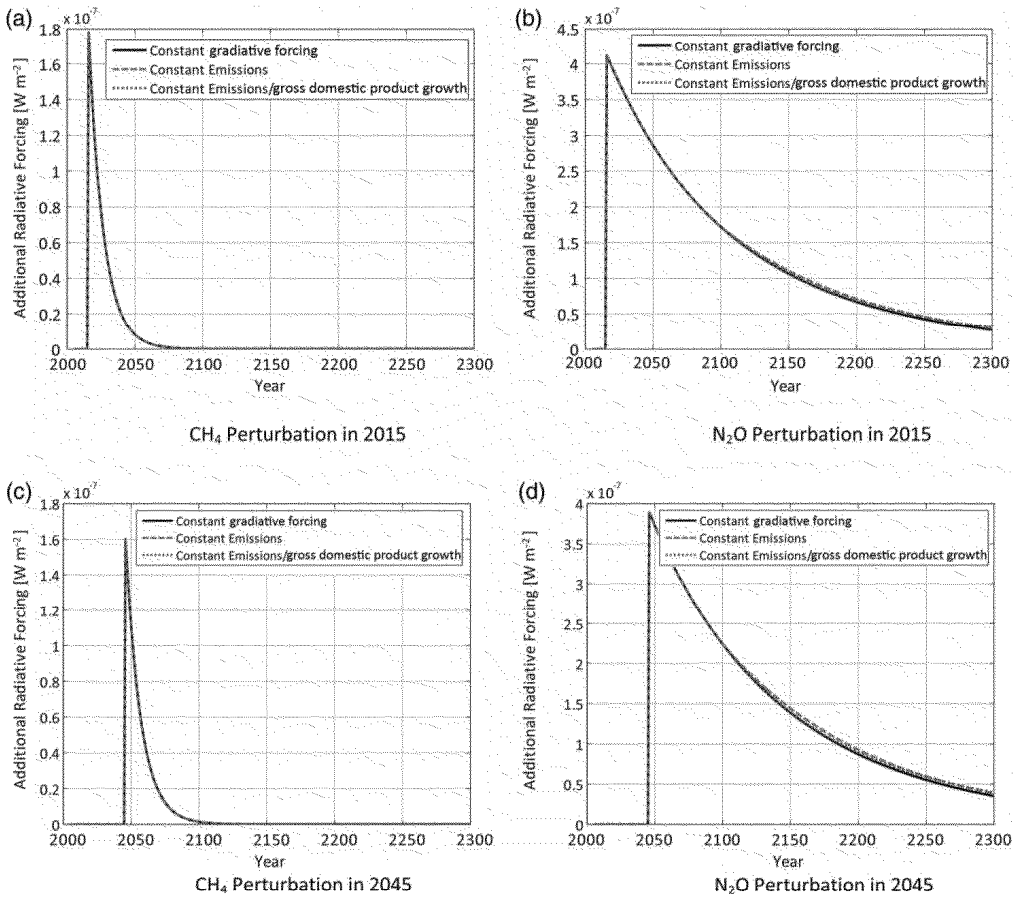

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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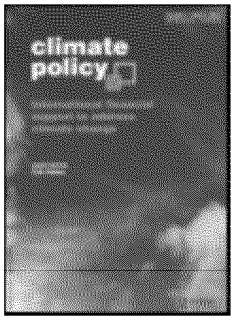

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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Benefit–cost analysis can serve as an informative input into the policy-making process, but only to the degree it characterizes the major impacts of the regulation under consideration. Recently, the US, amongst other nations, has begun to use estimates of the social cost of CO_2 (SC-CO_2) to develop analyses that more fully capture the climate change impacts of GHG abatement. The SC-CO_2 represents the aggregate willingness to pay to avoid the damages associated with an additional tonne of CO_2 emissions. In comparison, the social costs of non-CO_2 GHGs have received little attention from researchers and policy analysts, despite their non-negligible climate impact. This article addresses this issue by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. By extending existing integrated assessment models, it is possible to develop a set of social cost estimates for these gases that are consistent with the SC-CO_2 estimates currently in use by the US federal government.

Policy relevance

Within the benefit–cost analyses that inform the design of major regulations, all Federal agencies within the US Government (USG) use a set of agreed upon SC-CO_2 estimates to value the impact of CO_2 emissions changes. However, the value of changes in non-CO_2 GHG emissions has not been included in USG policy analysis to date. This article addresses that omission by developing a set of social cost estimates for two highly prevalent non-CO_2 GHGs, methane and nitrous oxide. These new estimates are designed to be compatible with the USG SC-CO_2 estimates currently in use and may therefore be directly applied to value emissions changes for these non-CO_2 gases within the benefit–cost analyses used to evaluate future policies.

Keywords: integrated assessment; non-CO_2 GHGs; social cost of carbon

1. Introduction

The social cost of CO_2 (SC-CO_2) is a measure of the monetary value of the damages occurring both within and outside economic markets as the result of an additional unit of CO_2 emissions. Specifically, it represents society's aggregate willingness to pay to prevent future impacts that occur when one additional unit of CO_2 is emitted into the atmosphere in a particular year. Estimates of SC-CO_2

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therefore provide a way to value changes in CO_2 emissions in benefit–cost analyses (BCAs) of policy alternatives. Without an estimate of the SC-CO_2, the benefits of mitigating the climate change impacts from CO_2 emissions would implicitly be valued at zero in BCAs, thereby significantly weakening the information provided by such analyses. Since 2009, the US Federal Government (USG) has used a set of agreed-upon SC-CO_2 estimates in the BCAs used to evaluate major regulations that impact CO_2 emissions (USG, 2010), including over 30 regulatory actions to date. The USG SC-CO_2 estimates are also increasingly being used in analysis and discussions outside the USG (e.g. by states, regional organizations, other nations, international organizations, NGOs, and academic researchers)[1] and have even figured in several recent public hearings and court cases (e.g. Keohane, 2010a, 2010b).

Although CO_2 is the primary anthropogenic GHG, other GHGs such as methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are also important contributors to climate change. The combined effect of all GHGs accumulated in the atmosphere is to increase the Earth's radiative forcing, which is the amount of energy from the Sun that is trapped in the Earth's atmosphere and therefore acts to warm the planet and change the climate. In 2011, the atmospheric CO_2 concentration contributed 64% of overall radiative forcing, while CH_4 and N_2O accounted for approximately 23% (Myhre et al., 2013). Non-CO_2 GHGs, notably CH_4 and N_2O, therefore contribute significantly to the negative impacts on human well-being from climate change. Furthermore, several recent studies have shown that consideration of non-CO_2 GHGs, particularly CH_4 and N_2O, is important for the design of cost-effective climate policy (Reilly et al., 1999; Tol, Heintz, & Lammers, 2003; Weyant, De La Chesnaye, & Blenford, 2006).

The monetary value of changes in emissions of non-CO_2 GHGs has not been included in USG policy analysis to date. This shortcoming prevents the development of accurate and comprehensive assessments of potential regulatory alternatives by the USG and others that rely on the USG SC-CO_2 estimates (Kopp & Mignone 2012; Marten & Newbold, 2012). For example, fossil fuels (e.g. coal and natural gas) have different compositions of GHG emissions across gases when considering the entire process of extraction, production, transmission, and combustion. Thus, if a regulation is anticipated to cause an industry to substitute between fuels, analysts may be providing inadequate information to decision makers and the public about its benefits if only the welfare implications of direct CO_2 emissions are considered while ignoring changes in CH_4 and other GHG emissions (Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2011).

A key reason for the value of non-CO_2 GHG emissions impacts not being included in USG analyses so far is that existing estimates of the social cost of non-CO_2 GHGs presented in the literature are inconsistent with USG SC-CO_2 modelling assumptions. For example, the recent US Environmental Protection Agency BCA of new pollution standards for the oil and natural gas industry concluded that, because they are not consistent with the USG SC-CO_2, 'the methane climate benefit estimates available in the current literature are not acceptable to use to value the methane reductions finalized in this rulemaking' (USEPA, 2012). This article seeks to address that gap by developing a new set of social cost estimates for CH_4 and N_2O (SC-CH_4 and SC-N_2O, respectively) that are fully consistent with the modelling assumptions underlying the current USG SC-CO_2 estimates. This article also develops an approach to extending the models used by the USG to generate estimates of the social cost of additional GHGs that are consistent with the latest USG estimates of the SC-CO_2.

It is important to note at the outset that by restricting attention to the derivation of social cost estimates consistent with the USG SC-CO_2 estimates, any limitations that apply to inputs and modelling

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assumptions underlying the USG SC-CO_2 estimates (e.g. Arrow et al., 2013; Kopp & Mignone 2012; Marten, 2011; O'Neil, 2010; Warren, Mastrandrea, Hope, & Hof, 2010) also apply to the SC-CH_4 and SC-N_2O estimates derived here. Thus, while it is anticipated that the USG will continue to improve the models and data it uses to estimate the SC-CO_2, this article focuses on the more immediate task of developing a set of consistent estimates for the social cost of other GHG emissions so that they need not be implicitly assigned a value of zero in USG policy analyses.

The remainder of the article is organized as follows. Section 2 presents an overview of the USG SC-CO_2 estimation approach and how it compares to the existing literature on the social cost of non-CO_2 GHGs, including a discussion of some of the critiques of the approach. Section 3 presents the approach for estimating the SC-CH_4 and SC-N_2O in a manner consistent with the USG SC-CO_2 estimates. Section 4 presents the results and a comparison of the relative social costs to the previous literature and the global warming potential (GWP)-based metric that is often used as an approximation in the absence of direct estimates, and Section 5 provides concluding remarks.

2. Background

In 2009–2010 the USG formed an interagency working group to develop a set of SC-CO_2 estimates for use by all Executive Branch agencies to value marginal changes in CO_2 emissions in regulatory impact analyses (USG, 2010). The goal of this exercise was to improve the accuracy and consistency with which agencies value marginal changes in CO_2 emissions. Before the release of these estimates, CO_2 emissions changes were valued in some but not all regulatory analyses, and the SC-CO_2 estimates used by different agencies varied substantially. The USG recently updated their estimates for the SC-CO_2 by employing new versions of the three underlying integrated assessment models (IAMs), but leaving the original estimation approach and underlying assumptions unchanged (USG, 2013). This section provides a brief overview of the estimation approach and assumptions used by the USG for estimating SC-CO_2, describes some critiques of the approach by other researchers, and discusses the existing literature on the social cost of non-CO_2 GHGs.

2.1. USG SC-CO_2 estimation approach

To estimate the SC-CO_2 the USG used three IAMs that couple simplified models of atmospheric gas cycles and climate systems with highly aggregate models of the global economy and human behaviour to capture the effects that GHG emissions, through their effect on the climate, have on human welfare. Within IAMs, the modelling that guides the transition from emissions into climate impacts is based on scientific assessments, while the mapping of climate impacts into changes in human welfare is based on economic research that has studied the effect of climate on various market and non-market sectors. Nordhaus and Boyer (2000) provide a very informative and detailed description of how such models are developed.[2]

The three models used by the USG are those that feature most prominently in the published social cost of carbon literature: the Dynamic Integrated Climate and Economy (DICE) (Nordhaus, 2008; Nordhaus & Boyer, 2000), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2006b, 2008), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff, Hepburn, & Tol, 2009; Tol, 2002a, 2002b, 2009) models. The USG chose to use the IAMs'

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climate system submodels and the functions that map climate change into economic damages as implemented by the model developers, but adopted a common set of input assumptions for equilibrium climate sensitivity, discount rates, global population, economic output, and GHG emissions projections. The remainder of this section provides a brief description of these common assumptions and the steps used to calculate the SC-CO_2 estimates. Interested readers can find more details in the USG's 2010 technical support document (USG, 2010).

2.1.1. Reference socio-economic-emissions scenarios

The USG selected five scenarios of economic output, population, and GHG emissions projections using results from the 2009 Stanford Energy Modeling Forum exercise number 22 (EMF-22). Four of the scenarios are based on baseline runs from global economic models (MERGE, MESSAGE, MiniCAM, and IMAGE) and span a range of emissions projections and plausible outcomes for future population and economic output absent significant global action to address climate change. These scenarios allowed for internally consistent forecasts of economic output, population, and emissions for the years 2000–2100. The fifth scenario used by the USG is based on the average of the 550 ppm CO_2e stabilization runs for each of the four models from which baseline scenarios were selected to represent potential action by the rest of the world absent US action. Across the five scenarios, atmospheric CO_2 concentrations in 2100 ranged from approximately 450 to 890 ppm (550–1130 ppm in CO_2e). Over the time horizon, the forecasts of the average growth rate for global per capita economic output ranged from 1.5% to 2.0% per year, and the average global population growth rate ranged from 0.4% to 0.5% per year. To run the IAMs through the year 2300, the USG extrapolated the selected EMF scenarios using the following assumptions: starting in 2100 the population growth rate declines linearly to zero in 2200; starting in 2100 the growth rate of economic output per capita declines linearly to zero in 2300; for all years after 2100 the growth rate of the carbon intensity of the global economy (CO_2 emissions/economic output) remains constant at its 2090–2100 average; starting in 2100 net land-use CO_2 emissions decline linearly to zero in 2200; and for all years beyond 2100 non-CO_2 radiative forcing anomalies remain constant at their 2100 levels.

Several limitations of the simplifying assumptions underlying the USG approach to scenario development have been discussed by other researchers. O'Neil (2010) pointed out that the selected EMF scenarios do not reflect the full range of outcomes that appear in other studies in the literature, and Kopp and Mignone (2012) suggested that the selected scenarios may effectively over-sample the peaks of the distributions. As for the extrapolations, while running the models out for multi-century time horizons is not necessary for relatively short-lived GHGs like CH_4, it is important for understanding the impacts of long lived GHGs such as CO_2 and N_2O that will affect human welfare well beyond 2100. As emphasized by O'Neil (2010) and Kopp and Mignone (2012), the state of the world beyond 2100 is highly uncertain and the scenario extrapolation approach taken by the USG represents only one of many possibilities. Furthermore, the extrapolations for each component of the scenarios (economic output, population, emissions) are separate and nothing ensures internal consistency within the scenarios past 2100. As shown by Marten and Newbold (2012), the temporal decomposition of damages for a perturbation of CO_2 and N_2O are relatively similar in shape and therefore the general findings of studies that explore the sensitivity of the SC-CO_2 to these assumptions should also be applicable to the SC-N_2O.

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2.1.2. Equilibrium climate sensitivity

In reduced-form IAMs, the speed and magnitude of temperature change for a given emissions projection are influenced largely by the 'equilibrium climate sensitivity' (ECS) parameter. The ECS represents the long-term global average temperature response to a level of radiative forcing associated with a sustained doubling of atmospheric CO_2 concentration (around 550 ppm). To represent the uncertainty in the responsiveness of the climate system to changing atmospheric conditions, the USG used a probability distribution for the ECS parameter of the form suggested by Roe and Baker (2007). The USG calibrated the parameters of the probability distribution to have a median equal to 3 8C, two-thirds probability that the ECS lies between 2 and 4.5 8C, which was intended to be consistent with the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) consensus statement about the ECS (Meehl et al., 2007). The distribution was truncated from above at 10 8C. This specification of the ECS distribution is retained to maintain consistency with the USG estimates of the SC-CO_2, but it is noted that the recently released AR5 by the IPCC has revisited the equilibrium climate sensitivity and revised the range downwards to 1.5–4.5 8C and no longer provides a most likely value (Collins et al., 2013). The ultimate effect of updating the ECS distribution to be consistent with the IPCC AR5 findings will depend heavily on the central tendency selected for the distribution.

2.1.3. Discount rates

Because the damages from an additional tonne of CO_2 emissions occur over many decades, the discount rate, which reflects the tradeoff between present and future consumption, plays a critical role in estimating the SC-CO_2. In light of disagreement in the literature regarding the appropriate discount rate to use in this context and uncertainty about future conditions that impact the discount rate, the USG used three constant discount rates intended to span a plausible range: 2.5%, 3%, and 5% per year. It is worth noting that the debate regarding not only the appropriate discount rate but also its time path is ongoing (Arrow et al., 2013; Dasgupta, 2008). While the appropriate value for the discount rate will presumably remain an area of active debate for some time to come, there appears to be agreement that the use of a constant discount rate over long time horizons with uncertain changes in the consumption per capita growth is not theoretically consistent. This article uses the same three constant discount rates as the USG estimation process, but in Appendix C results are reported from a series of sensitivity analyses using a Ramsey discounting approach. Similar to Marten and Newbold (2012), it is found that applying Ramsey discounting using plausible values for the components of the consumption discount rate gives a range of social cost estimates that is broadly consistent with the range of results obtained using the constant discount rates.

2.1.4. Calculating the SC-CO_2

The process to estimate the SC-CO_2 for emissions in year t has four steps. First, each model is used to forecast monetized impacts associated with the baseline path of emissions, economic output, and population. Second, each model is re-run with an additional unit of CO_2 emissions in year t to forecast monetized impacts for all years beyond t along this perturbed path of emissions. Third, the marginal damages in each year are calculated as the difference between the monetized impacts forecast in steps 1 and 2. Finally, the resulting path of marginal damages is discounted and summed to calculate

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the present value of the marginal damages in the year when the additional unit of emissions used to perturb the model is emitted.

The USG repeated this process with each model, discount rate, and socio-economic-emissions scenario for each decade between 2010 and 2050. Because the ECS parameter is modelled probabilistically, and because PAGE and FUND incorporate uncertainty in other model parameters, the final output from each model run represents a distribution over the SC-CO_2 in each year. These distributions were estimated using 10,000 simulations in each model run. Therefore, the exercise produced 45 separate distributions of the SC-CO_2 for a given emissions year, based on the three models, three discount rates, and five socio-economic-emissions scenarios considered. To provide a range of estimates that reflects this uncertainty but still emphasizes the central tendency, the distributions from each of the models and scenarios were equally weighted and combined to produce three separate probability distributions for the SC-CO_2 in a given year, one for each assumed discount rate. Four SC-CO_2 estimates were selected from these three probability distributions to reflect the global damages caused by one tonne of CO_2 emissions. Three estimates are based on the average SC-CO_2 across the three models and five socio-economic-emissions scenarios for the 5%, 3%, and 2.5% discount rates, respectively. The fourth value is the 95th percentile of the SC-CO_2 distribution at the 3% discount rate, and was chosen to represent potential higher-than-expected impacts from anthropogenic GHG emissions.

2.2. Existing estimates of the social cost of non-CO_2 GHG emissions

A significant limitation of the aforementioned USG interagency process is that the social costs of non-CO_2 GHG emissions were not estimated. Therefore, as an alternative to applying direct estimates for the social costs of non-CO_2 GHG emissions in the primary BCA, several recent USG regulatory analyses have approximated the benefits of non-CO_2 GHG emissions reductions in sensitivity analyses by transforming the non-CO_2 GHG emissions to 'CO_2-equivalents' using estimates of the GWP for the GHG in question and then using the USG SC-CO_2 for valuation (e.g. US EPA, 2012, 2013).

Gas comparison metrics, such as the GWP, have been designed to measure the impact of different GHGs relative to CO_2, where the point of comparison along the pathway from emissions to monetized damages (depicted in Figure 1) may differ across measures. The GWP, in particular, is designed to measure the additional radiative forcing (i.e. the amount of energy absorbed by atmospheric concentrations of GHGs) from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years). The GWP and other gas-comparison metrics are problematic as an SC-CO_2 scalar in BCA, as the remaining linkages in the pathway depicted in Figure 1 are complex and non-linear. Marten and Newbold (2012) demonstrate that using the GWP to adjust SC-CO_2 estimates to capture the impact of non-CO_2 gases provides a significant improvement over the implicit assumption that they are zero when such benefits are left unquantified, but may still underestimate mitigation benefits. Alternative gas comparison metrics that compare GHGs at different points in the chain of

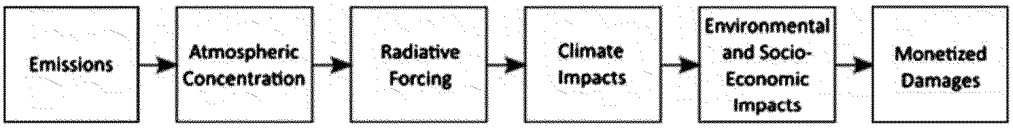

Figure 1 Path from GHG emissions to monetized damages

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causation (e.g. global temperature change potential (Shine, Fuglestvedt, Hailemariam, & Stuber, 2005), peak commitment temperature (Smith et al., 2012), temperature proxy index (Tanaka, O'Neill, Rokityanskiy, Obersteiner, & Tol, 2009)) have also been shown to be imperfect substitutes for direct estimates.

Several researchers have directly estimated the social cost of non-CO_2 GHG emissions using IAMs, although the number of such estimates is small compared to the large number of SC-CO_2 estimates available in the literature. Among these previous direct estimates there is considerable variation in the model versions and input assumptions used. See Table 1 for a summary of the 11 non-CO_2 studies published to date.

As shown in Table 1, the estimates cover emissions years from 1990 to 2050, although the specific perturbation year is not stated in all studies. The studies also cover a wide range of constant and variable discount rate specifications and consider a range of baseline socio-economic and emissions scenarios that have been developed over the last 20 years. Finally, some studies in the literature have chosen not to report the social cost estimates directly. Instead, they opt to report only the 'global damage potential', which is a ratio of the social cost of gas X to the SC-CO_2. Normalizing the SC-CH_4 or

TABLE 1 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Model	Time horizon	Discount rate	Emissions year	Scenario[a]	Climate sensitivity
Reilly and Richards (1993)	N/A	140 years	2, 5, 8%	1990	N/A	N/A
Fankhauser (1994)	N/A	230 years	Ramsey	1991–2030	IS92[b]	N/A
Kandlikar (1995)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Kandlikar (1996)	N/A	100 years	0, 2, 6%	N/A	IS90a,d	3 8C
Hammitt et al. (1996)	N/A	2200	1, 3, 5%	1995–2015	IS92a,c,e	1.5, 2,5, 4.5 8C
Tol (1999)	FUND 1.6	2100	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Tol et al. (2003)	FUND 1.7	2200	0, 1, 3, 5, 10%	1995–2014	IS92a	2.5 8C
Hope (2005)	PAGE95	2200	Ramsey	2000	SRES A2	Probabilistic, mode of 3 8C
Hope (2006a)	PAGE2002	2200	Ramsey	2001	SRES A2	Probabilistic, mean of 3 8C
Waldhoff et al. (2011)	FUND 3.5	3000	Ramsey	2010–2019	FUND, SRES A1B, A2, B1, B2	2, 3, 4.5 8C
Marten and Newbold (2012)	DICE2007 w/ MAGICC	2300	Ramsey, 2.5, 3, 5%	2010–2050	EMF-22 MiniCAM Base	Probabilistic,median of 3 8C

[a]IS90 scenarios are based on the IPCC First Assessment Report (IPCC, 1990); IS92 scenarios are based on the IPCC Supplementary Report (IPCC, 1992); SRES scenarios are based on the IPCC Special Report on Emissions (IPCC, 2000); the FUND scenario is the default scenario in the FUND model; EMF-22 scenarios are based on results from Stanford's Energy Modeling Forum's 22nd exercise (Clarke et al., 2009).[b]The particular IS92 scenario used was not specified.

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SC-N_2O estimate using the SC-CO_2, in part, controls for differences in the modelling to allow for a better comparison with other estimates in the literature.

Fankhauser (1994) was one of the first to develop estimates of the average SC-CH_4 and SC-N_2O for emissions in the 2010 and 2020 decades given a 100-year time horizon for climate change damages. Kandlikar (1995) and Hammitt, Jain, Adams, and Wuebbles (1996) also developed estimates of SC-CH_4 and SC-N_2O for a single socio-economic-emissions scenario and using constant discount rates. Tol et al. (2003) and Hope (2005, 2006a) developed estimates for the SC-CH_4 in 2000 using the FUND and PAGE models, respectively. Waldhoff, Anthoff, Rose, and Tol (2011) used a newer version of the FUND model to develop estimates of the social cost of marginal CO_2, CH_4, N_2O, and SF_6 emissions for the average year in the 2010 decade. While they considered only a single emissions period, they conducted a wide range of sensitivity analyses including four socio-economic-emissions scenarios from the IPCC special report on emissions (IPCC, 2000) in addition to the default FUND scenario. In Section 4, the specific results of these previous studies are discussed with a comparison to the estimates obtained in the present study.

The above-mentioned previous studies provide a basic understanding of the relative social costs of different GHGs but do not provide sufficient information about how this relationship changes over time. Marten and Newbold (2012) used an IAM that couples the climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) with economic components of the 2007 version of William Nordhaus' DICE model to directly estimate the social cost of marginal CO_2, CH_4, and N_2O emissions. They estimated the annual social costs for the years 2010–2050 along a single socio-economic-emissions pathway given uncertainty about the equilibrium climate sensitivity parameter. An advantage of their approach is that through the use of a more detailed, yet still relatively simple, climate model their results are not affected by over-simplification of temperature response or atmospheric chemistry, which have been shown to have non-negligible effects on the estimates of social costs (Marten, 2011; Warren et al., 2010).

The work of Marten and Newbold (2012) uses many of the assumptions used by the USG in its estimation of SC-CO_2, including discount rates, the equilibrium climate sensitivity distribution, and post-2100 socio-economic and emissions extrapolations. However, they focus on only one of the three models and one of the five socio-economic-emissions scenarios used by the USG. Furthermore, they use a different climate sub-model, which leads their estimate of the SC-CO_2 to be different from the USG estimate, even for the same IAM and scenario combination. Therefore, although these studies, including Marten and Newbold (2012), have increased our understanding about the relative social costs of GHG emissions, they have not provided a set of estimates that are entirely consistent with the USG SC-CO_2 estimates. In Section 4, the estimates derived in this article are compared with those of Marten and Newbold (2012) to more clearly demonstrate the similarities and differences in the two sets of estimates for SC-CH_4 and SC-N_2O.

3. Estimating the social cost of non-CO_2 GHGs consistent with USG SC-CO_2

The primary obstacle in estimating the social cost of non-CO_2 GHG emissions in a manner consistent with the USG SC-CO_2 estimates is that not all of the IAMs used include explicit representations of the non-CO_2 gases of interest. This section describes the degree to which non-CO_2 GHGs are currently

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represented in the default versions of DICE, PAGE, and FUND, and then discusses how they are amended to estimate the social cost of these gases.

3.1. Representation of non-CO_2 GHGs in DICE, PAGE, and FUND

The FUND model explicitly considers CH_4, N_2O, and SF_6 in addition to CO_2. The model uses one-box atmospheric gas cycle models for these gases, with geometric decay towards pre-industrial levels. For CH_4 and N_2O, FUND estimates the additional radiative forcing imposed by the atmospheric buildup of these gases using the simplified expressions presented in Chapter 6 of the IPCC's Third Assessment Report (TAR) (Ramaswamy et al., 2001). FUND also augments the TAR expression for the additional radiative forcing from CH_4 to account for the influences of stratospheric water vapour and tropospheric ozone changes. Because FUND uses CH_4 and N_2O emissions as inputs and internally computes their impact on the climate system, it is possible to directly estimate the social cost of those gases without modifying the model.

In the DICE model, the only GHG that is explicitly represented is CO_2; an exogenous radiative forcing projection is used to account for the impact of all other gases on the climate. To develop an exogenous radiative forcing pathway consistent with the emissions scenarios used to estimate the SC-CO_2, the USG decomposed the default DICE exogenous radiative forcing vector into CH_4, N_2O, F-gases, aerosols, and other residual forcing components. The USG then replaced the radiative forcing attributed to CH_4, N_2O, and F-gases with estimates associated with the EMF-22 scenarios. As non-CO_2 emissions are not a direct input into DICE, it is not possible to simply perturb the emissions projection and re-run the model to obtain a forecast of additional damages.

The 2002 version of the PAGE model, which was used by the USG in developing its first set of estimates (USG, 2010), includes an atmospheric model for CH_4 and SF_6, but represents the effects of other non-CO_2 GHGs in an exogenous radiative forcing projection. Presumably to simplify the process and maintain consistency with DICE, the USG did not use PAGE's internal CH_4 component. Instead, the same exogenous radiative forcing projection was used for the effect of CH_4, N_2O, and F-gas emissions as was used for DICE. Since then, a N_2O component has been added to the PAGE model, although in the recent 2013 SC-CO_2 update the USG maintained the approach of using the same single exogenous forcing projection as was applied to DICE (USG, 2013). Therefore PAGE, as implemented by the USG, faces the same limitations as DICE with respect to estimating the social costs of marginal non-CO_2 emissions that are consistent with the USG SC-CO_2 estimates. For these reasons, computing estimates for the social cost of non-CO_2 gases in DICE and PAGE requires either replacing the climate component of these models with a more complete representation, as was done with DICE by Marten and Newbold (2012), or deriving an estimate of the path of additional radiative forcing that would result from a perturbation of the gas in question. This article uses the latter approach for DICE and PAGE, as the former would represent a substantial change to the underlying IAMs and would have implications for the SC-CO_2 estimates, making this work inconsistent with the USG SC-CO_2 estimates currently used in regulatory analysis.

3.2. Estimating the social cost of non-CO_2 GHGs in DICE and PAGE

The process used in this article to estimate the social cost of non-CO_2 GHGs in DICE and PAGE as implemented by the USG requires first generating a forecast of the additional radiative forcing

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associated with a perturbation of a non-CO_2 gas's emissions in a single year, and then adding this radiative forcing perturbation to each model's exogenous radiative forcing projection. To determine the additional radiative forcing associated with the emission perturbation, there is a need to model the change in atmospheric concentration and the radiative forcing associated with the additional concentration. For both CH_4 and N_2O, a simple one-box atmospheric gas cycle model with a constant decay rate is used to estimate the atmospheric concentration of each gas based on its assumed emissions. The use of a one-box gas cycle for CH_4 and N_2O with constant decay follows the approach used by the IPCC to compute GWPs (Forster et al., 2007) and the FUND model (Anthoff & Tol, 2013). In both the baseline and the perturbed case, the contribution of the gas to the global radiative forcing anomaly is determined by the forcing relationships presented in the IPCC TAR (Ramaswamy et al., 2001), which were not updated by the IPCC in AR4. The incremental radiative forcing is defined by the difference between the baseline forcing path and the emissions path that includes a one tonne perturbation in a given year. Next, the path of additional radiative forcing is added to the stream of exogenous radiative forcing in each IAM to estimate the climate damages in the perturbed scenario. These damages are then compared to the baseline damages to determine the social cost of gas X (SC-X). Specifically, the process is as follows:

1. Run the IAM as described in the SC-CO_2 technical support document (USG, 2010) to estimate baseline damages.
2. Estimate the baseline atmospheric concentration for gas X.
3. Estimate the baseline radiative forcing contribution of gas X.
4. Perturb the stream of gas X emissions by one tonne in year t.
5. Estimate atmospheric concentration for gas X in the perturbed scenario.
6. Estimate the radiative forcing contribution of gas X in the perturbed scenario.
7. Compute the incremental radiative forcing as the difference between the results of steps 3 and 6.
8. Add the additional radiative forcing from step 7 to the exogenous radiative forcing path used in the IAM in step 1.
9. Re-run the IAM to compute the damages along the perturbed emissions path.
10. Compute the social cost of gas X for emission year t as the present value of the difference in damages estimated in steps 1 and 9.

Two practical issues associated with implementation are worth noting. First, while the SC-X estimates are associated with a one tonne perturbation, to avoid computational rounding error a 1 Mt perturbation is used and then the resulting change in damages is scaled to get the average effect per tonne. Experiments conducted by Griffiths et al. (2012) to assess the applicability of the SC-CO_2 to non-marginal emission changes show that the average per tonne SC-CO_2 estimate is relatively constant over large differences in perturbation size. Additional experiments in the context of this article found that alternative perturbation sizes do not significantly change the average one tonne social cost estimate. Second, the additional radiative forcing due to the emissions perturbation is computed based on an annual time step, but because DICE and PAGE use longer time steps the average radiative forcing over the time step is added to the model's exogenous radiative forcing vectors.

The remainder of this section describes the procedure for modelling the incremental radiative forcing of a perturbation for CH_4 and N_2O, and explores the sensitivity of these projections to

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two issues. First, it evaluates whether the simple one-box gas cycle model with a constant decay rate produces a close approximation to the forecasts of future atmospheric CH_4 and N_2O concentrations based on a more sophisticated climate model. Second, it explores the sensitivity of the results to the method used for extrapolating non-CO_2 emissions from 2100 to 2300. This is important, because the USG did not specify a particular set of emissions pathways for each constituent gas, instead assuming only that non-CO_2 radiative forcing remains constant past 2100. Such a situation could arise from a myriad of possible individual gas projections and the USG did not specify which it was assuming.

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3.3. Methane

A simple one-box atmospheric gas cycle model for methane specifies the concentration in year t, $C_t^{CH_4}$ [ppb], such that

$$C_t^{CH_4} = C_{t-1}^{CH_4} + d_{CH_4}(C_{pre}^{CH_4} - C_{t-1}^{CH_4}) + g_{CH_4}E_{t-1}^{CH_4}, \tag{1}$$

where d_{CH_4} defines the rate of decay, $C_{pre}^{CH_4}$ [ppb] is the pre-industrial atmospheric concentration, and g_{CH_4} [ppb/Mt] converts emissions, $E_{t-1}^{CH_4}$ [Mt], from mass to atmospheric volume. The mass to volume conversion factor is g_{CH_4} ¼ 0.3597 ppb/Mt and $C_{pre}^{CH_4}$ ¼ 700 ppb, following the IPCC TAR. The rate of decay is set to d_{CH_4} ¼ 1/12 following the IPCC AR4 stated CH_4 lifetime of 12 years. The iteration begins in the year 2006 using the emissions from the EMF-22 scenario (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used so that $C_{2005}^{CH_4}$ ¼ 1774 ppb.

The contribution of atmospheric methane to global radiative forcing, denoted $Q_t^{CH_4}$, is defined using the relationship in Table 6.2 of the IPCC TAR:

$$Q_t^{CH_4} = f\ 0.036\ \left(C_t^{CH_4} - C_{pre}^{CH_4}\right) - \left[f(C_t^{CH_4}, C_{pre}^{N_2O}) - (C_{pre}^{CH_4}, C_{pre}^{N_2O})\right], \tag{2}$$

where $C_{pre}^{N_2O}$ [ppb] is the pre-industrial atmospheric concentration of nitrous oxide and

$$f(C^{CH_4}, C^{N_2O}) = 0.47 \ln\left[1 + 2.01 \times 10^{-5}(C^{CH_4}C^{N_2O})\right]^{0.75} + 5.31 \times 10^{-15}C^{CH_4}(C^{CH_4}C^{N_2O})^{1.52}. \tag{3}$$

The function in expression (3) accounts for the overlapping absorption bands of CH_4 and N_2O, thereby reducing their effective absorption. Parameter f is used to proxy for indirect effects of CH_4 that include the enhancement of stratospheric water vapour and tropospheric ozone changes. Following the IPCC AR4, an enhancement effect of 40% (25% from tropospheric ozone change and 15% for stratospheric water vapour enhancement) is used, such that f ¼ 1.4. The pre-industrial concentration of N_2O is set consistent with the IPCC TAR, such that $C_{pre}^{N_2O}$ ¼ 270 ppb.

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A key simplification in this approach is the constant decay rate used in the atmospheric gas cycle model. As discussed by IPCC Working Group I in Chapter 4 of the TAR, the lifetime of methane emissions in the atmosphere depends on temperature and the concentrations of CO, NOx, and other VOCs in the atmosphere (Ehhalt et al., 2001). Sensitivity analysis is used to understand the potential implications of ignoring these interactions by comparing the incremental atmospheric concentration projected by the simple model described above to the analogous projection from the climate model MAGICC,[3] which, while still relatively simple, incorporates these interactions between the lifetime of CH_4 in the atmosphere and the other gases and climate variables. This exercise uses CH_4 emissions from the EMF-22 MiniCAM reference scenario and considers a one tonne perturbation of CH_4 in 2015. It is noted that these results are robust across alternative emissions levels.[4]

Figure 2(a) presents the projected average decadal increment to atmospheric concentrations using both the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. At the time of the perturbation (2015), the inter-annual time step of MAGICC allows for an uptake of the additional emissions into the atmosphere, whereas the strict annual time step of the simple model causes a year to pass before the change is registered. After the initial year, the models originally differ by around 15%. This difference falls to under 10% within the first decade, with the faster effective growth in the simple model causing its additional concentration to eventually fall below that of MAGICC.

The difference in the incremental radiative forcing from the perturbation between the simple model and MAGICC is also of importance. Although MAGICC relies on similar equations to derive the radiative forcing of atmospheric CH_4 concentrations, it differs in the way it handles indirect effects of CH_4 on tropospheric ozone and stratospheric water vapour, in addition to including other temperature-related feedbacks. Figure 2(b) presents the average additional radiative forcing per decade attributed to the 2015 CH_4 perturbation in both models. The average increase in radiative forcing over the decade is considered because this is the input required by DICE due to its ten-year time step and therefore a more relevant comparison (PAGE requires a similar multi-year average). When considering the average additional radiative forcing over the decade, the initial difference in concentration between MAGICC and the simple model has a minimal effect and the difference in radiative forcing between the two models is less than 2% over the first two decades. However, this difference grows to –18% over the subsequent two decades. This escalation in the difference is in part due to the use of a constant decay rate in the simple model, whereas MAGICC takes into account the growing atmospheric concentrations of other gases and increasing atmospheric temperature, which increase the lifetime of atmospheric CH_4.

To understand the effect that this difference would have on an estimate of the SC-CH_4, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of CH_4, as computed using both the simple model and MAGICC, is added to the exogenous forcing projection. As above, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 2 presents the results of this experiment. In line with the results comparing the radiative forcing perturbations above, the two approaches produce similar social cost estimates for emissions in 2015, where additional analysis has shown these results to hold with PAGE as well. The impact of assuming a constant decay rate is greater further out into the future, due to the projected increase in the atmospheric concentration of other relevant gases and atmospheric temperature that are accounted for in MAGICC, and the social cost

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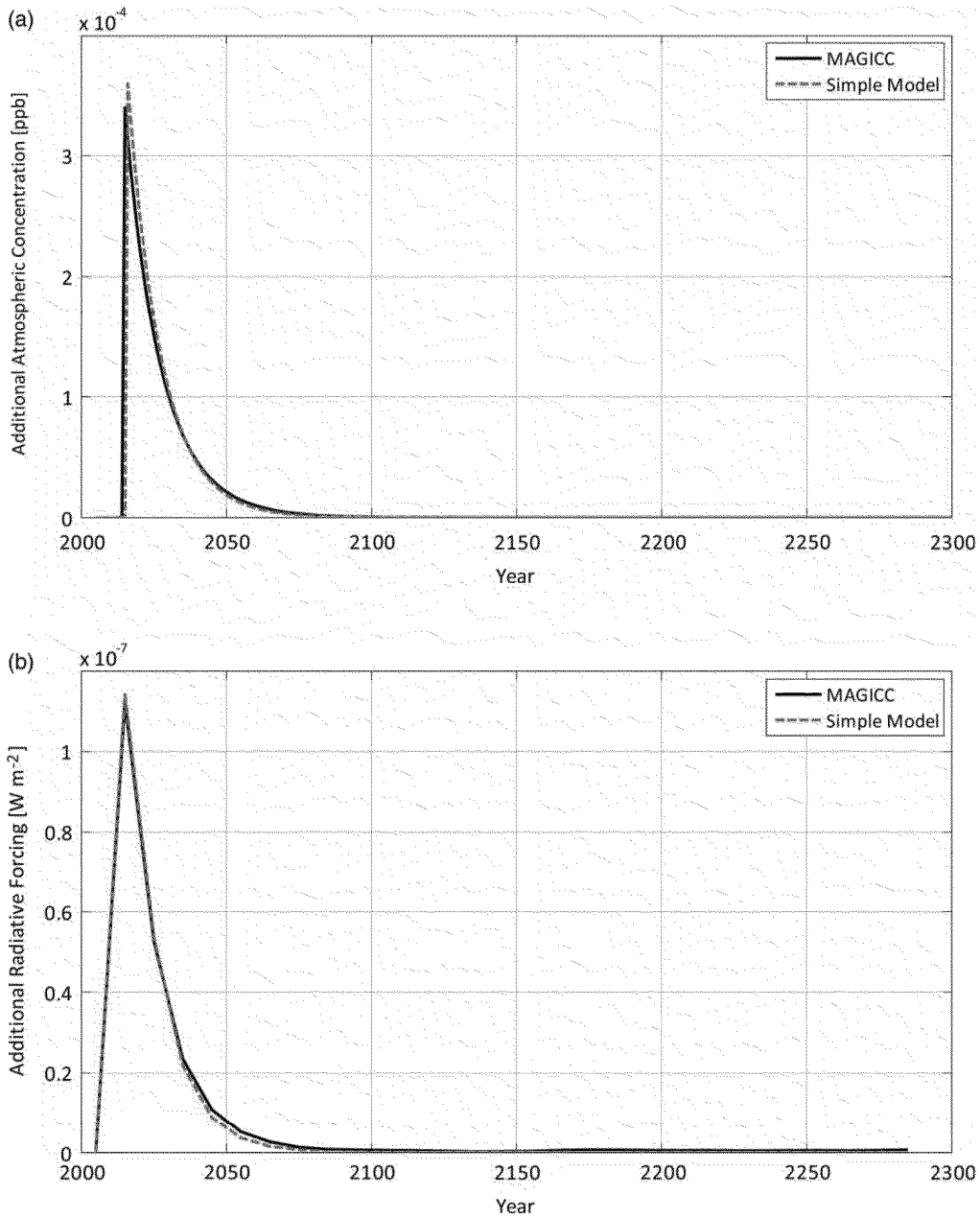

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

estimates begin to diverge for later emissions years. For the same reason, the two approaches will show greater differences for lower discount rates that give increased weight to future time periods. While over-simplification of the climate system can, in some circumstances, have significant effects on

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TABLE 2 Effect of CH_4 gas cycle model on SC-CH_4 (2007$ per tonne CH_4): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	1135	1183	2 4%
	3.0%	822	851	2 3%
	5.0%	349	354	2 2%
2045	2.5%	2490	2707	2 8%
	3.0%	1933	2084	2 7%
	5.0%	956	1006	2 5%

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social cost estimates (e.g. Marten 2011), the near-term differences based on this simplification seem relatively small considering the precision of such social cost estimates.

3.4. Nitrous oxide

The simple one-box atmospheric gas cycle model for N_2O takes a similar form to the model used for CH_4, such that the concentration of nitrous oxide in year t, $C_t^{N_2O}$ [ppb], is specified as

$$C_t^{N_2O} = C_{t-1}^{N_2O} + d_{N_2O}(C_{pre}^{N_2O} - C_{t-1}^{N_2O}) + g_{N_2O}E_{t-1}^{N_2O}, \tag{4}$$

where d_{N_2O} is the rate of decay, and g_{N_2O} [ppb N_2O/Mt N] converts emissions, $E_{t-1}^{N_2O}$ [Mt N], from mass to atmospheric volume. Following the IPCC AR4, the mass to volume conversion factor is g_{N_2O} ¼ 0.2079 ppb N_2O/Mt N and the rate of decay is d_{N_2O} ¼ 1/114 based on a 114-year lifetime. As with CH_4, the iteration begins in the year 2006 using the emissions from the EMF-22 scenarios (linearly interpolated between the decadal values reported), therefore requiring an assumption about the atmospheric concentration in 2005. The value from the Advanced Global Atmospheric Gases Experiment network as reported in the IPCC AR4 is used, such that $C_{2005}^{N_2O}$ ¼ 319 ppb.

The contribution of atmospheric N_2O to global radiative forcing, denoted $Q_t^{N_2O}$, is defined using the relationship in Table 6.2 of the IPCC TAR, such that

$$Q_t^{CH_4} = 0.12 \left[C_t^{N_2O} - C_{pre}^{N_2O} - [f(C_{pre}^{CH_4}, C_t^{N_2O}) - f(C_{pre}^{CH_4}, C_{pre}^{N_2O})] \right], \tag{5}$$

where $f(C^{CH_4}, C^{N_2O})$ is defined in expression (3).

As with CH_4, a key simplifying assumption is the constant decay rate used in the simple gas cycle model (and potentially the time it takes the gas to become well mixed within the atmosphere). As discussed in the IPCC TAR, the decay rate of N_2O will depend on the atmospheric concentration of N_2O and so will not be constant in reality. To examine the extent to which this impacts the results of the simple model, an analogous set of experiments as conducted for CH_4 were performed. Given future

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N_2O emissions based on the EMF-22 MiniCAM reference scenario, a one tonne N_2O perturbation in 2015 is considered. Figure 3(a) shows the projected atmospheric concentration increase from the perturbation using the simple one-box model with a constant decay rate and the MAGICC model with a variable decay rate. This comparison illustrates that the simple model tracks the output of MAGICC well for the entire 300-year time horizon. Outside the initial perturbation year, the two projections do not differ by more than 2% within the first century, with the largest difference occurring in the perturbation year, for the same reasons as with CH_4.

Figure 3(b) presents the estimates of average additional radiative forcing per decade as a result of the N_2O perturbation using both models. The additional radiative forcing from the N_2O perturbation in the one-box model is forecast to be slightly lower (7%) in the first decade compared to MAGICC. Subsequently, the difference is within 2% through to 2300.

As with CH_4, to assess the effect that this difference would have on the SC-N_2O, an experiment was conducted using the DICE model in which the additional forcing from a one tonne perturbation of N_2O computed using both the simple model and MAGICC is added to the exogenous forcing projection. As before, the MiniCAM scenario is used and the sensitivity of the results to both perturbation year and discount rate is examined. Table 3 presents the results of this experiment. As the comparisons of the projected radiative forcing perturbations would suggest, the difference between the social cost estimates for the two approaches is relatively small. In contrast to the case of CH_4, here an increase in the discount rate increases rather than decreases the divergence between the estimates due to the greater weight being placed on the earlier years when the radiative forcing perturbations have a slightly higher degree of divergence.

3.5. Effect of post-2100 non-CO_2 radiative forcing assumptions

The EMF-22 socio-economic-emissions scenarios used by the USG include years only up to 2100, while the USG ran the IAMs out to 2300. Therefore, additional assumptions were required to extrapolate the scenarios beyond 2100. For the purposes of this study, the most important of these assumptions is that non-CO_2 radiative forcing will remain constant at its 2100 level until 2300. Such a broad assumption was sufficient for the purposes of the USG in estimating the SC-CO_2. However, estimating the social cost of non-CO_2 GHGs requires explicit projections of baseline emissions of non-CO_2 gases in order to correctly determine the effect of the perturbation. The USG's broad assumption regarding the extrapolation of non-CO_2 gases is therefore problematic as constant non-CO_2 radiative forcing post 2100 may occur in an infinite number of ways. For instance, one way to achieve this outcome is to assume that emissions of each non-CO_2 gas falls to a level equal to its respective rate of decay in 2100. This assumption would keep atmospheric concentrations, and in turn radiative forcing, constant. Based on the simple gas cycle models laid out in the earlier sections this implies that, for gas X,

$$E_t^X = \frac{-d_X(C_{pre}^X - C_{2100}^X)}{g_X} \forall t \ . \ 2100. \tag{6}$$

To put this assumption into context, the solid lines in Figure 4(a) and (b) present the emissions paths for CH_4 and N_2O, respectively, under the MiniCAM EMF-22 reference scenario extrapolated using

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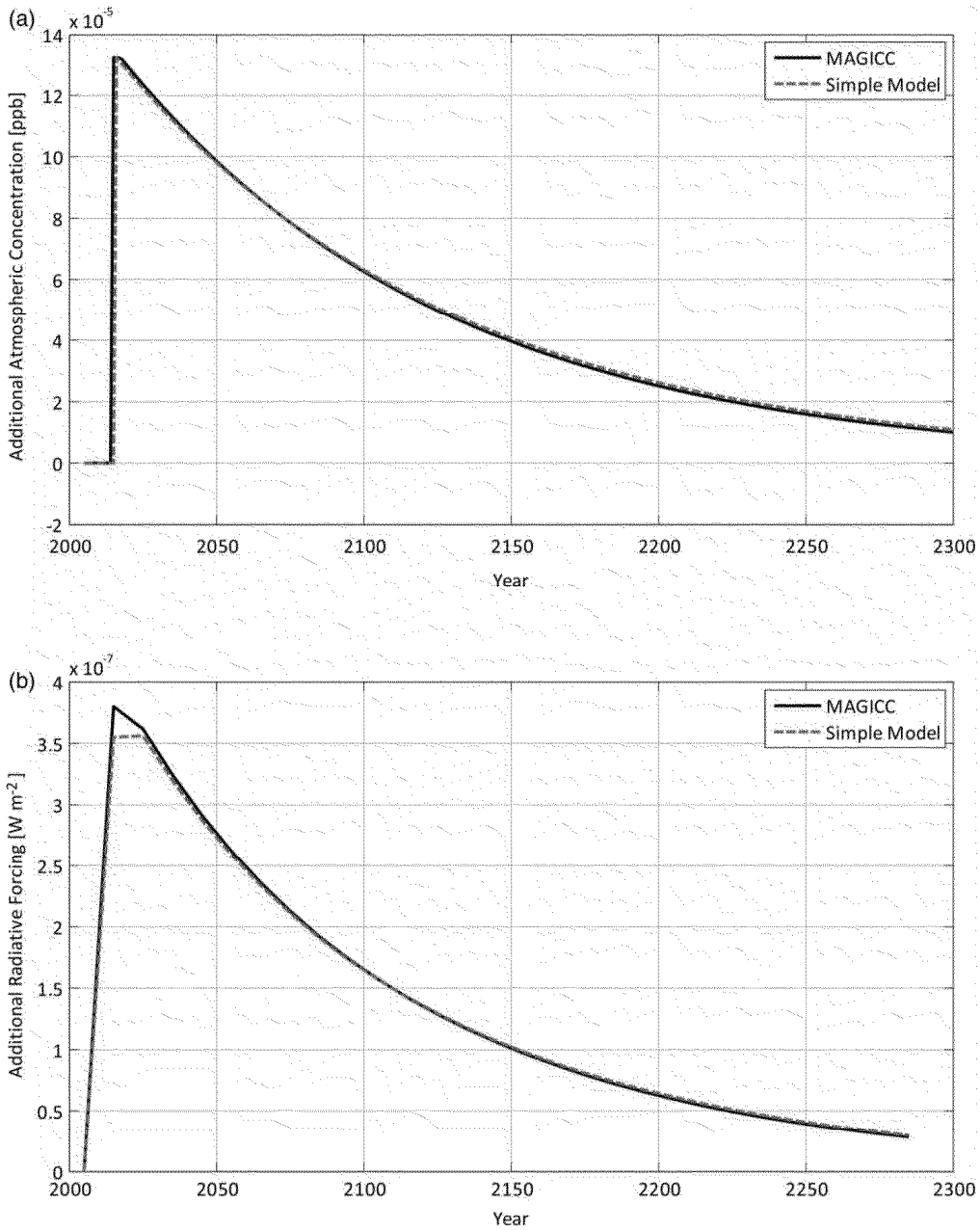

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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TABLE 3 Effect of climate model on SC-N_2O (2007$ per tonne N_2O): DICE2010, MiniCAM

Perturbation year	Discount rate	Simple model	MAGICC	Percent difference
2015	2.5%	19,689	19,819	2 1%
	3.0%	12,390	12,525	2 1%
	5.0%	3,346	3,419	2 2%
2045	2.5%	36,968	37,358	2 1%
	3.0%	25,030	25,427	2 2%
	5.0%	8,280	8,528	2 3%

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expression (6), while the dashed lines show two alternative extrapolation approaches, one where emissions are held constant at their 2100 level and one that assumes emissions intensity (emissions/economic output) continues to decline at the same rate forecast by the EMF-22 scenario in 2090–2100 (dotted line). This latter alternative is analogous to the USG assumption regarding industrial CO_2 emissions. The two alternatives will not result in the radiative forcing contribution of gas X remaining constant post-2100, but do not in themselves violate the assumption that overall non-CO_2 radiative forcing remains constant. Noteworthy is the fact that the assumption in (6) is almost analogous to keeping CH_4 emissions constant at their 2100 levels, whereas for N_2O the assumption requires a sudden decrease in emissions of over 35%.

While Figure 4 illustrates that these three extrapolation approaches can lead to vastly different projections for emissions after 2100, the relevant comparison is how these assumptions affect the additional radiative forcing from a perturbation of the gas and in turn the SC-X estimates. Figure 5(a–d) present the additional radiative forcing resulting from a one tonne perturbation based on the simple model presented in Sections 3.1 and 3.2. Figure 5(a) and (b) demonstrates the difference for a perturbation in 2015, whereas Figure 5(c) and (d) represents perturbations in 2045. For CH_4, the cumulative radiative forcing from the projection over the time horizon differs by less than 0.001%, even for a

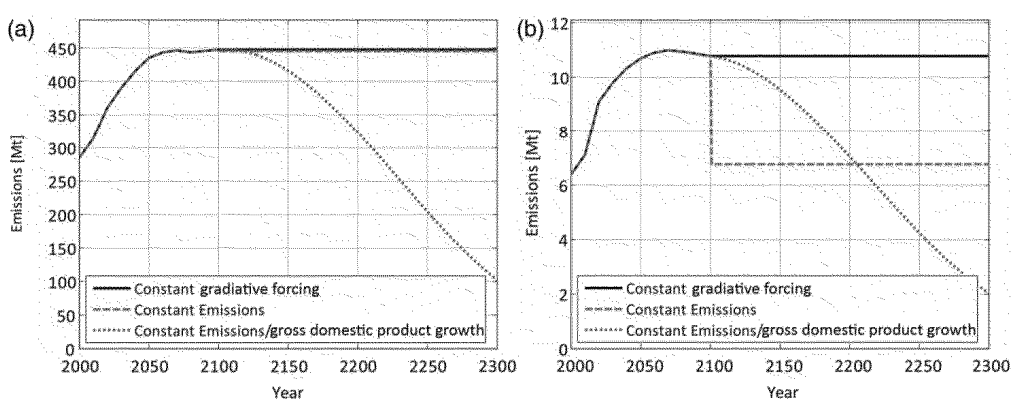

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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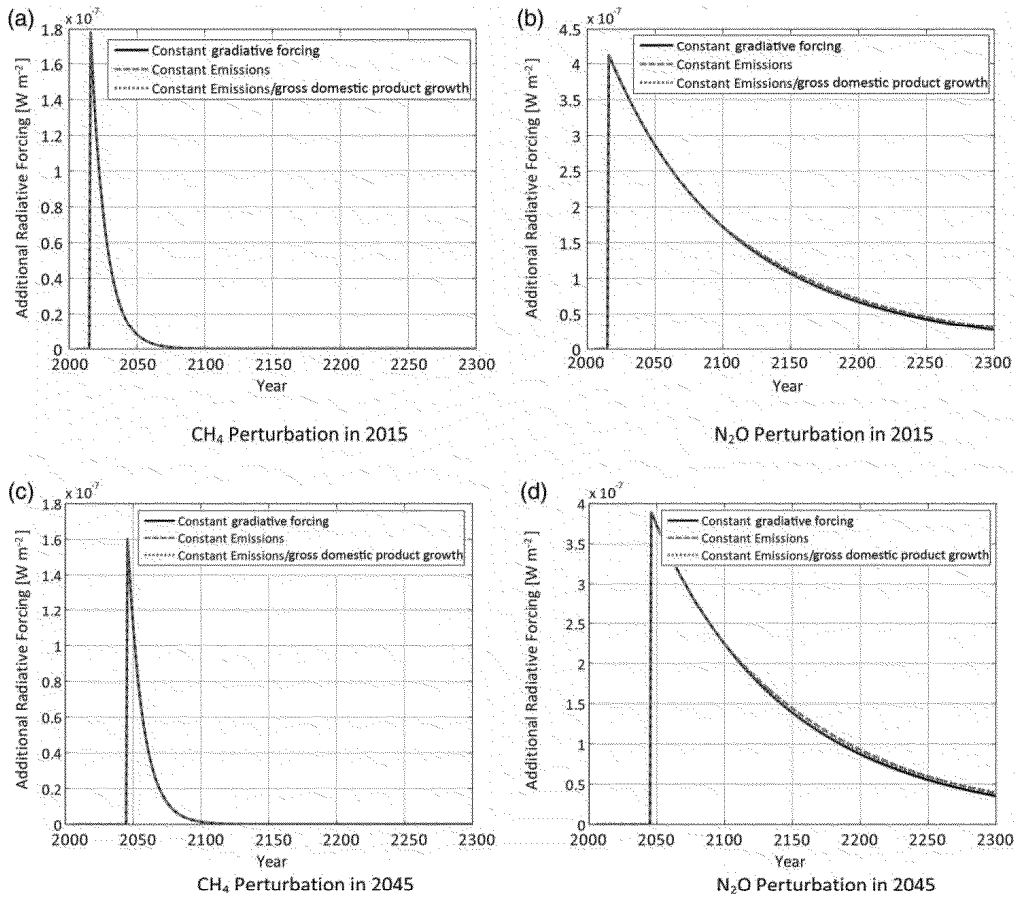

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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perturbation in 2045. Accordingly, the relevant annual difference is smaller even than one-thousandth of a percent. This result occurs because of the short atmospheric lifetime of the gas, which renders assumptions regarding CH_4 emissions after 2100 unimportant for near-term perturbations. Post-2100 emissions will have a larger effect in the case of N_2O, which has a much longer atmospheric residence time. However, even for a perturbation in 2045, the difference in cumulative additional radiative forcing is less than 2.5% across the extrapolation assumptions.

To examine the impact of these assumptions on SC-CH_4 and SC-N_2O, an experiment was conducted using the DICE model based on the EMF-22 MiniCAM socio-economic-emissions scenario. The results of this experiment are presented in Table 4 for the perturbation year 2045 (noting that the extrapolation method will have greater impact on future emissions years). As may be seen, the relatively short atmospheric lifetime of CH_4 leads to a situation in which post-2100 assumptions do not affect SC-CH_4 estimates, even in 2045. For the longer-lived gas N_2O, in emission year 2045, where the effect of the post-2100 extrapolation approach would be largest, the difference across the three

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TABLE 4 Effect of post-2100 extrapolation on the 2045 SC-X (2007$ per tonne): DICE2010, MiniCAM

Gas	Discount rate	Constant RF	Constant emissions	Constant emissions intensity growth
CH_4	2.5%	2,490	2,490	2,490
	3.0%	1,933	1,933	1,933
	5.0%	956	956	956
N_2O	2.5%	36,968	36,588	36,662
	3.0%	25,030	24,837	24,868
	5.0%	8,280	8,261	8,263

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assumptions is less than 1% and the projections are equivalent to two significant digits. Therefore, in the remainder of this article, non-CO_2 emissions are extrapolated past 2100 using expression (6) to ensure that the gas-specific contribution to overall radiative forcing remains constant in the simple model. While additional study may lead to improvements of long-term forecasts of CH_4 and N_2O emissions and possible correlations, compared to the paths in Figure 5(a), the very minimal effect of such assumptions on the social cost estimates suggests the impact of such efforts would be minimal in this context.

4. Results

For FUND, the social cost of non-CO_2 GHGs is estimated by perturbing the paths of emissions directly, while for DICE and PAGE the approach presented in Section 3 is used. In both cases, all additional assumptions made by the USG are applied, including the five EMF-22 socio-economic-emissions scenarios, the Roe and Baker (2007) distribution for the equilibrium climate sensitivity, and constant discount rates of 2.5%, 3.0%, and 5.0%. Following the USG, the estimates for the expected social cost are averaged across scenarios and models, with each model and scenario given equal weight. Estimates are not combined across discount rates, and a fourth estimate is included representing the 95th percentile when using the 3.0% discount rate. By using the same assumptions and procedures as the USG, estimates of the SC-CO_2 derived in this article are identical to the values used in US Federal rule making. Specifically, these estimates are equivalent to the recent 2013 update of the USG SC-CO_2, which revised the original 2010 USG upwards based on new versions of the IAMs used. The non-CO_2 results, as well as the USG SC-CO_2 estimates, are presented in Table 5 for emissions years 2020 and 2050.[5] Results for additional years, and the results of sensitivity analyses using Ramsey discounting, may be found in Appendix B and C, respectively.

As expected, considering their higher radiative efficacy, the social costs associated with a tonne of CH_4 and N_2O emissions are substantially higher than for CO_2. The values are higher at lower discount rates, although the impact of the discount rate is lower for CH_4 given its relatively short lifetime. Similar to CO_2, the social cost estimates for CH_4 and N_2O increase over time as the climate and economic systems become more stressed, although the growth rate of the social cost estimate may differ between the gases, as discussed in the following.

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TABLE 5 SC-X (2007$ per tonne)

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CO_2	12	43	64	128
	CH_4	550	1,200	1,600	3,200
	N_2O	4,800	15,000	22,000	41,000
2050	CO_2	26	71	97	220
	CH_4	1,400	2,500	3,100	6,900
	N_2O	11,000	27,000	38,000	74,000

To better understand how the social costs of CH_4 and N_2O compare to CO_2, Table 6 presents the global damage potentials corresponding to the social cost estimates from Table 5. (The disaggregated results, by model and scenario, for 2020 are provided in Appendix B.) As explained in Section 2, the global damage potential for gas X is the ratio of SC-X to SC-CO_2, and therefore by construction captures all the important linkages between emissions and monetized climate change damages (to the degree they are captured by the IAMs) directly within the gas comparison metric. As noted by Frankhauser (1994), this is preferred to the commonly used GWP gas comparison metric, which only measures the additional radiative forcing from a perturbation of a given GHG relative to a perturbation of CO_2 over a specific time horizon (e.g. 100 years) and ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages.

The global damage potential of CH_4 decreases with the discount rate due to the relatively shorter atmospheric lifetime. This difference in atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO_2 than the SC-CH_4. This finding is robust across the models. The estimates in Table 6 also present the same result for N_2O in the aggregate case, although this characteristic is not consistent across the models or the previous literature. Based on the disaggregated results (presented in Appendix B), the results from the DICE model suggests the global damage potential for N_2O increases with lower discount rates due to a lower effective decay rate over the relevant time horizon for N_2O than CO_2. This result is consistent with previous findings by Marten and Newbold (2012). However, for FUND the opposite is seen to hold. Waldhoff et al. (2011) show that this result is primarily due to the inclusion of increased production in the agriculture and forestry sectors from CO_2 fertilization effects. At lower discount rates these benefits place a greater downward

TABLE 6 Global damage potential

Year	Gas	5.0% mean	3.0% mean	2.5% mean	3% 95th percentile
2020	CH_4	46	29	25	25
	N_2O	397	359	353	317
2050	CH_4	52	36	32	31
	N_2O	414	388	387	338

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impact on the SC-CO_2, thereby lowering the global damage potential. If one were to remove those impacts from the FUND model the global damage potential for N_2O becomes relatively insensitive to the discount rate. One would expect the role of the discount rate in determining the global damage potential in PAGE to be the same as in DICE, but the results suggest that this is not the case. It seems most likely that this is because the PAGE model has only ten time steps to cover the entire time horizon, which results in very large, up to 100-year, time steps further out in time. As noted in Section 3, the additional radiative forcing from the N_2O perturbation is implemented as the average across the model's time steps. It seems that PAGE does not average radiative forcing over the time step for CO_2, which causes the global damage potential for N_2O to decrease with the discount rate. It is not clear if this result would hold if the size of the time steps in the model were reduced.

A comparison across models further highlights the importance of CO_2 fertilization impacts on the global damage potential. CO_2 emissions, and the resulting increase in atmospheric concentration, have the potential to increase yields in the agriculture and forestry sector. This characteristic is not shared by other GHG emissions. Accordingly, the FUND model, which explicitly captures this effect, exerts downward pressure on the SC-CO_2 that is not present for the SC-CH_4 and SC-N_2O, allowing for the possibility of substantially higher global damage potential estimates. The results based on the FUND model presented in this article exhibit this effect; however, the CO_2 fertilization effect is not explicitly modelled in DICE and PAGE and therefore they are found to produce lower estimates of the global damage potential. For example, using the 3% discount rate, the global damage potential for CH_4 as estimated by FUND ranges between 58 and 88 depending on the scenario, whereas it ranges from 19 to 28 for DICE and PAGE. As the DICE and PAGE models only consider two natural system impacts, temperature and sea level, if they do implicitly include potential CO_2 fertilization benefits, they are included by using the temperature anomaly as a proxy for the increasing atmospheric CO_2 concentration. Fertilization benefits would therefore be allowed to falsely accrue to perturbations of other GHG emissions besides CO_2. It is not clear the degree to which these models try to incorporate CO_2 fertilization effects and therefore the degree to which this issue is of concern.

Finally, the results in this article show that the 100-year GWP (25 for CH_4 and 298 for N_2O; Forster et al., 2007) probably provides an underestimate of the global damage potential of each gas, a finding consistent with previous studies by Marten and Newbold (2012) and Waldhoff et al. (2011). Unlike the GWP as calculated by the IPCC, the global damage potential will be dependent upon the year of the emissions perturbations, so the degree of underestimation varies by year. For CH_4, the global damage potential in Table 6 is 0–84% higher than the GWP in 2020, increasing to 24–108% in 2050. For N_2O, the global damage potential is 6–33% higher than the GWP in 2020, increasing to 13–39% in 2050. While inaccurate, using the GWP to convert emissions reductions into CO_2 equivalents that can be valued with the SC-CO_2 would probably provide a conservative estimate for the abatement benefits.

For the comparison above, the GWP estimates presented in the AR4 by the IPCC (Forster et al., 2007) were used to maintain consistency with the assumptions regarding the direct and indirect effect of CH_4 and N_2O concentrations within the modelling. The recent AR5 by the IPCC (Myhre et al., 2013) has increased the estimate of the indirect effects of CH_4, which gives a higher 100-year GWP for CH_4 of 28. A reduction in their estimate of the radiative efficacy of N_2O has decreased its 100-year GWP to 265. It is likely that updated modelling of the social cost estimates based on similar assumptions would maintain the finding that the GWP is an underestimate of the global damage potential.

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4.1. Comparison with previous estimates

For comparison, Table 7 presents the social cost estimates, when available, and the global damage potential estimates for CH_4 and N_2O from three recent studies in the literature whose features are more up to date and therefore more directly comparable with this study: Hope (2006a), Waldhoff et al. (2011), and Marten and Newbold (2012). A direct comparison to the longer list of studies presented in Table 1 is more difficult as they are based on models and socio-economic and emissions scenarios that were developed up to 20 years ago in a rapidly evolving field.

The social cost estimates presented in Table 5 are higher than the estimates in Hope (2006a) and Waldhoff et al. (2011) for CH_4, and in the range of Waldhoff et al. (2011) for N_2O. This result holds whether the comparison is made with the aggregate results in Table 5 or the disaggregated model-specific results. One reason for the significant difference in the SC-CH_4 estimates is that the earlier studies rely on older model versions (PAGE2002 and FUND3.5), neither of which include the indirect effects of CH_4 emissions on radiative forcing, but are included within this analysis. As noted in Section 3.3 the indirect effects of CH_4 are modelled as a 40% increase in its effective radiative forcing. The result of this change alone would likely be a greater than 40% increase in the SC-CH_4 due to the nonlinear damage functions. Furthermore, the assumptions regarding preference parameters in the main cases of Hope (2006a) and Waldhoff et al. (2011) lead to effective discount rates that are significantly higher than 3%. Other differences in input assumptions (e.g. equilibrium climate sensitivity, socio-economic emissions scenario) will also lead to differences, although these are likely to be of second-order importance given the relative similarity in the assumptions.

However, the results in Table 5 averaged across the combinations of the three models and five scenarios are relatively similar to those of Marten and Newbold (2012), which focused on a single scenario

TABLE 7 Previous estimates of the social cost of CH_4 and N_2O emissions

Study	Discount Rate	Emissions Year	Social cost (2007$/tonne X)[a]		Global damage potential (SC-X/SC-CO_2)	
			SC-CH_4	SC-N_2O	CH_4	N_2O
Hope (2006a)	Ramsey	2001	125	–	20	–
Waldhoff et al. (2011)[b]	Ramsey	2010–2019	265	7,616	26	738
			–	–	8–221	383–3,503
Marten and Newbold (2012)	2.5%	2020	1,500	26,000	23	403
		2050	3,500	50,000	32	444
	3%	2020	1,100	17,000	27	400
		2050	2,900	34,000	36	439
	5%	2020	550	4,900	42	380
		2050	1,500	12,000	53	415

[a]All values are discounted to the year of the emissions perturbation.
[b]The first row presents the base case and the second row presents the range found from sensitivity analysis (over socio-economic scenario, climate sensitivity, pure rate of time preference, climate sensitivity and CO_2 fertilization).

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and model. This result is in part based on the fact that both sets of results include the indirect effects of CH_4, use the same discount rates and equilibrium climate sensitivity distribution, and relatively similar scenarios. The estimates in this study are slightly higher for the SC-CH_4 and slightly lower for the SC-N_2O compared to Marten and Newbold (2012). Of particular interest is the specific comparison of this article's estimates based on DICE 2010 and the MiniCAM scenario to those of Marten and Newbold (2012) using the same scenario, discount rates, and equilibrium climate sensitivity but an the older 2007 version of the DICE model and a more complete climate sub-model. In this case, estimates for both the SC-CH_4 and SC-N_2O (presented in Appendix B) are notably lower. The myriad of differences between the model vintages and climate sub-models make it difficult to assess which differences are most important for explaining this relationship.

As previously noted, the global damage potential may provide a better value with which to compare across studies that estimate the social cost of non-CO_2 GHG emissions, as it helps to control for some of the underlying differences in assumptions across studies. For example, the global damage potential is far less sensitive to the discount rate used than the SC-X values themselves. However, the global damage potential does not address the lack of indirect CH_4 effects, as may be seen in the lower estimates of Hope (2006a) and Waldhoff et al. (2011). In these cases the exclusion of the 40% additional increase in radiative forcing from the indirect effects of the CH_4 perturbation explains the majority of the difference. In comparison to Marten and Newbold (2012), the results presented in Table 6 are relatively similar for CH_4 in both the aggregate and disaggregated results. For N_2O, similar results are found in the DICE estimates, but notable differences are found in how the aggregate results respond to the discount rate, due to the differences in this relationship between the models as noted above.

5. Concluding remarks

This article presents a simple and transparent approach to estimating the social cost of CH_4 (SC-CH_4) and N_2O (SC-N_2O) in a manner that is consistent with estimates of the social cost of CO_2 (SC-CO_2) already in use in benefit–cost analysis (BCA) for US Federal regulations. This approach is used to estimate the SC-CH_4 and SC-N_2O for the period 2010–2050. These directly modelled estimates are found to be larger than approximations of the social costs of these gases based on the application of common physical gas comparison metrics, such as global warming potentials (GWPs), to the SC-CO_2. This result generalizes the empirical findings of Marten and Newbold (2012) that using a GWP-based approximation approach will likely offer a conservative estimate of the social cost of non-CO_2 GHGs.

The social costs associated with emissions of non-CO_2 GHGs are substantial and should be included within the BCAs used to assess the overall welfare implications of policy alternatives. For example, by not including monetized values of the benefits from reducing CH_4 and N_2O emissions, the BCA for recent standards regulating the fuel efficiency and GHG emissions of light duty vehicles implicitly assigned them a value of zero (US EPA, 2010). However, the results of this article suggest that those reductions have benefits of US$85–493 million (2007$) for CH_4 and $1.5–12 million (2007$) for N_2O in the year 2020 alone. Failing to account for such impacts could limit the ability of the analysis to serve as a transparent and informative input into the decision-making process about the relative benefits and costs of regulatory alternatives. That said, by restricting the article to a derivation of social cost estimates consistent with the USG SC-CO_2 estimates, the myriad issues related to

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whether those estimates can themselves be improved are set aside.[6] Any limitations that apply to the USG SC-CO_2 estimates therefore also apply to the SC-CH_4 and SC-N_2O estimates derived here.

Supplemental data

Supplemental data for this article can be accessed 10.1080/14693062.2014.912981.

Notes

1. Examples include Minnesota's draft methodology for setting the value of a tariff to compensate solar panel owners for the surplus power they deliver to utilities (http://www.eenews.net/stories/1059992297, http://mn.gov/commerce/energy/images/DRAFT-MN-VOS-Methodology-111913.pdf), the Northwest Power and Conservation Council's symposium supporting the development of the 7th Power Plan (http://www.nwcouncil.org/energy/powerplan/7/symposiums/greenhouse/agenda), BCA of Canada's Heavy-duty Vehicle and Engine Greenhouse Gas Emission Regulations (http://canadagazette.gc.ca/rp-pr/p2/2013/2013-03-13/html/sor-dors24-eng.html), analysis of climate change projects at the Inter-American Development Bank (correspondence with Patrick Doyle, Senior Climate and Energy Officer, Structured and Corporate Finance Department), the International Monetary Fund's recent Energy Subsidy Reform report (http://www.imf.org/external/np/pp/eng/2013/012813.pdf), and Parry and Strand (2012).
2. An alternative approach for estimating the social cost of GHG emissions could be based on stated preference (SP) surveys designed to elicit respondents' maximum willingness-to-pay for various levels of GHG emission reductions (e.g. Longo, Markandya, & Petrucci, 2008; Soliño, 2010). This approach would not suffer from the difficulties associated with creating and parameterizing a numerical integrated assessment model. However, it would suffer from its own set of difficulties, including well-known general limitations that affect all SP studies including the potential for 'hypothetical bias' (e.g. Carson, 2012; Hausman, 2012; Kling, Phaneuf, & Zhao, 2012), plus difficulties that may be specific to this application stemming from the generally limited knowledge base regarding the potential climatic, biophysical, and especially economic impacts of GHG emissions on current and far future generations that most respondents will bring to the survey.
3. The fork of MAGICC version 5.3 included in Pacific Northwest National Laboratory's open source model GCAM version 2 (Calvin et al., 2009) is used without carbon cycle feedbacks and, unless otherwise specified, an equilibrium climate sensitivity of 3 8C. We note that sensitivity analysis found the general results of this side analysis to be robust to other values of the equilibrium climate sensitivity.
4. The EMF-22 scenario is extended past 2100 assuming that emissions stay constant at the 2100 level. This assumption is revisited later in this article.
5. The PAGE 2009 model restricts the user to representing the entire time horizon, in this case out to 2300, with only ten time steps. This leads to the unrealistic situation in a small number of simulations where the marginal unit of emissions can cause 'catastrophic' climate impacts to occur one period earlier, which could be 100 years earlier in some cases. We consider these occurrences to be a limitation of the model and drop them from the overall distribution of estimates. Appendix A contains further details about this issue.
6. In addition to the critiques previously cited, we point the interested reader to the work of Marten et al. (2013) and Oppenheimer (2013) for a review of literature that considers potential improvements in the assessment and valuation of climate change impacts.

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