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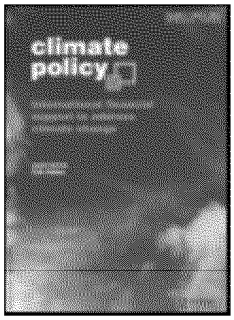

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Incremental CH_4 and N_2O mitigation benefits consistent with the US Government's SC-CO_2 estimates

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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

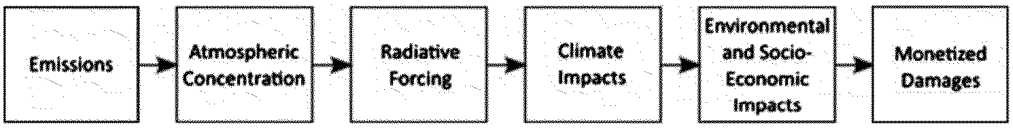

Figure 1 Path from GHG emissions to monetized damages

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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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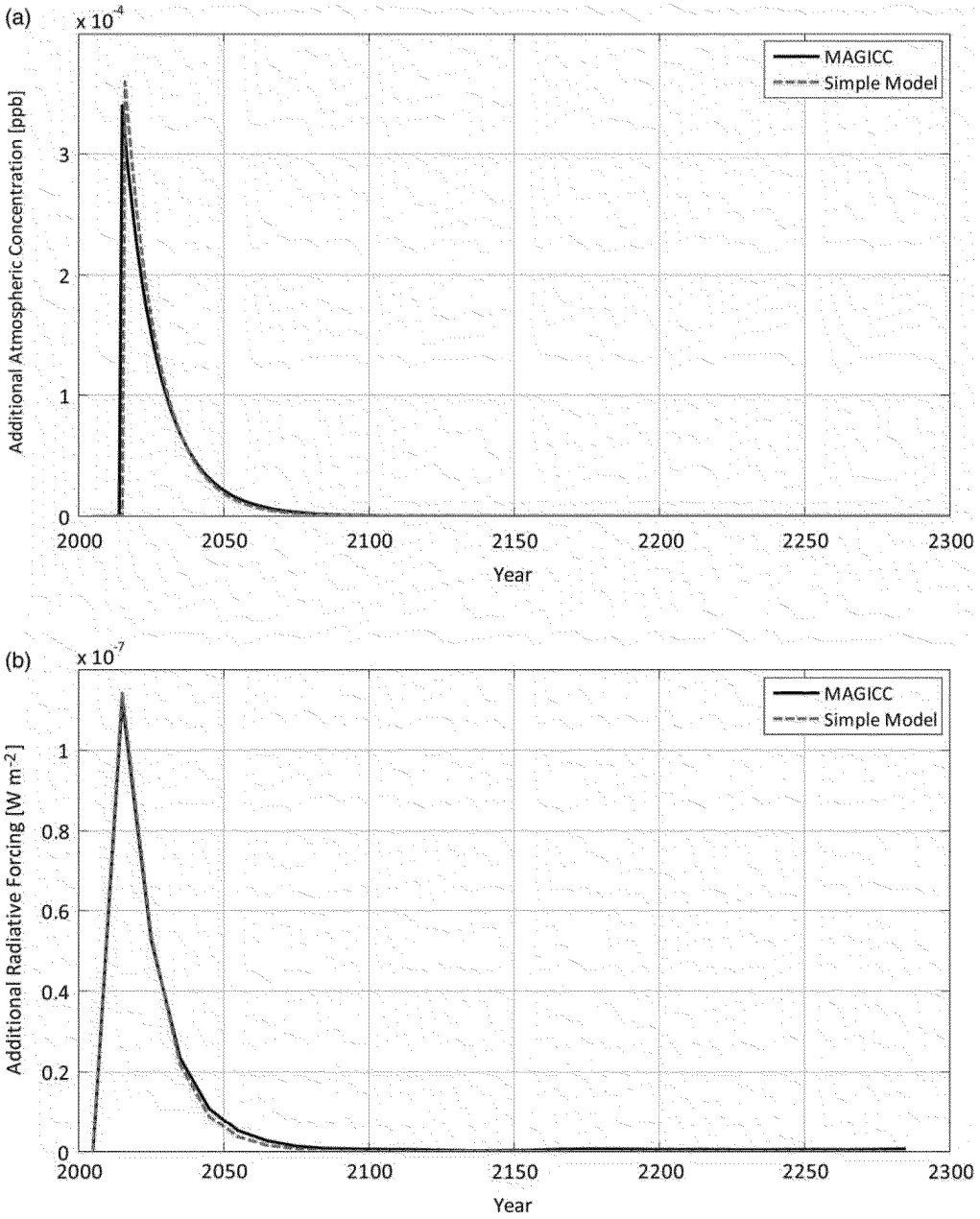

Figure 2 Effects of perturbation in 2015 CH_4 emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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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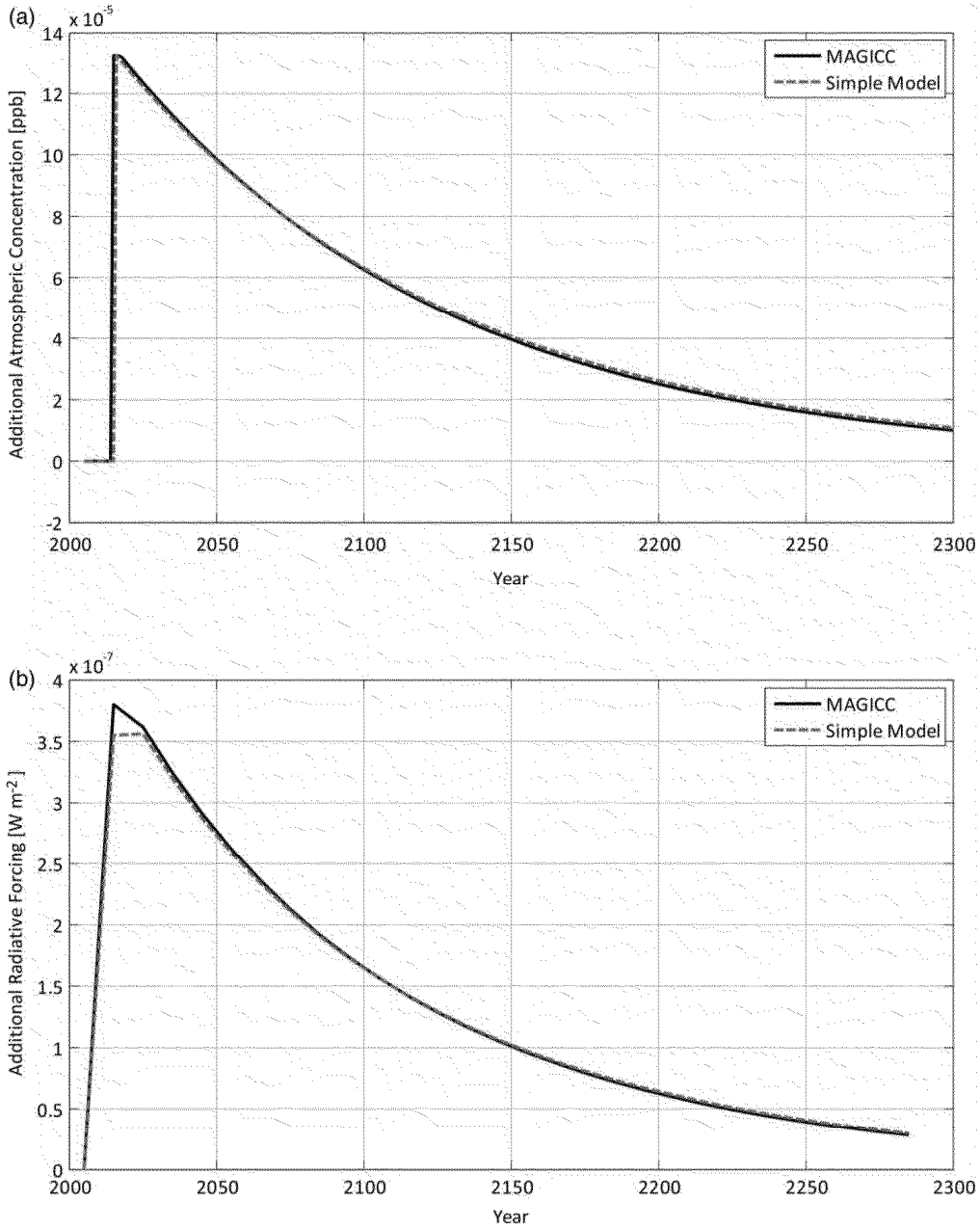

Figure 3 Effects of perturbation in 2015 N_2O emissions for simple model vs. MAGICC: (a) additional atmospheric concentration; (b) additional radiative forcing

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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

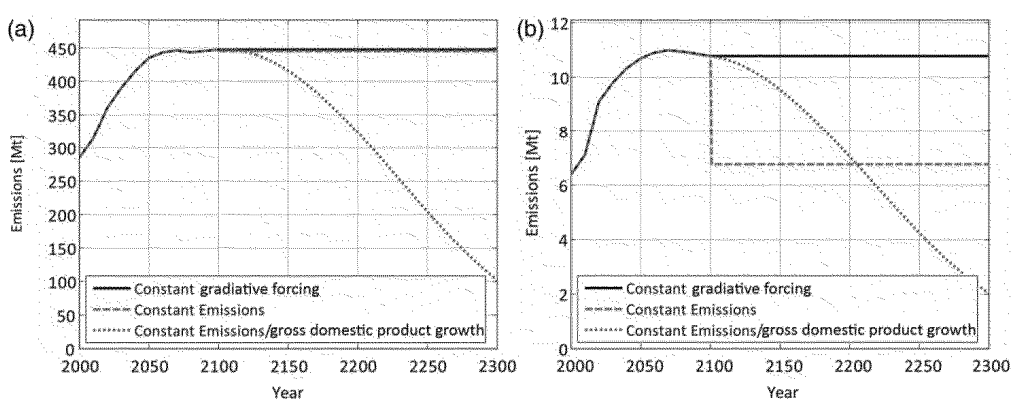

Figure 4 EMF-22 MiniCAM extended emissions scenario: (a) CH_4 emissions; (b) N_2O emissions

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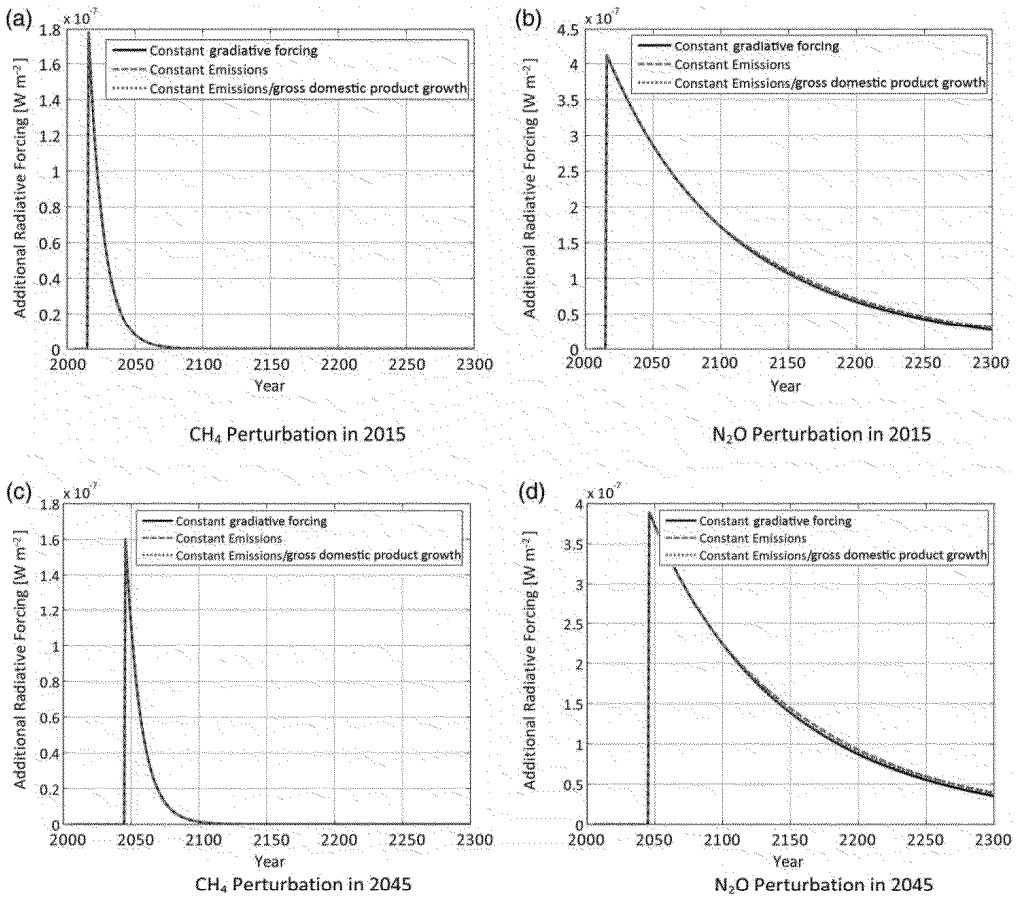

Figure 5 Effect of extrapolation approach on radiative forcing perturbation from simple model: (a) CH_4 perturbation in 2015; (b) N_2O perturbation in 2015; (c) CH_4 perturbation in 2045; (d) N_2O perturbation in 2045

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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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).

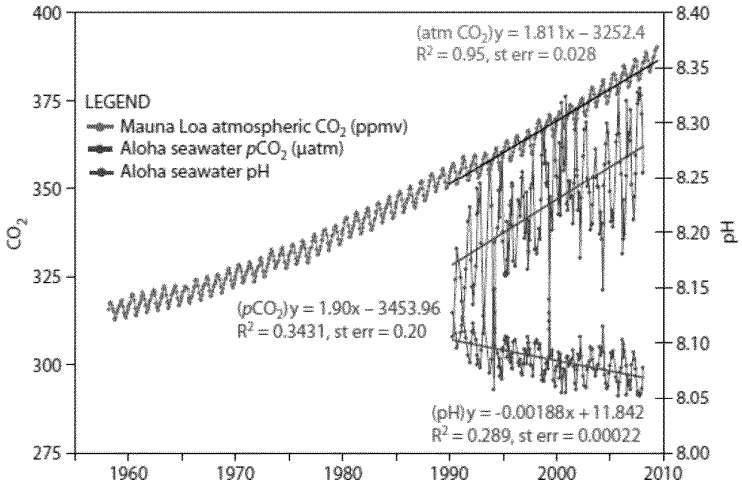

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the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

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).

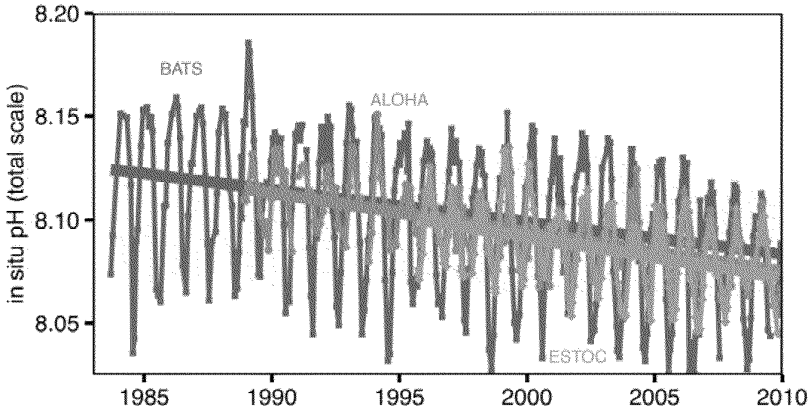

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (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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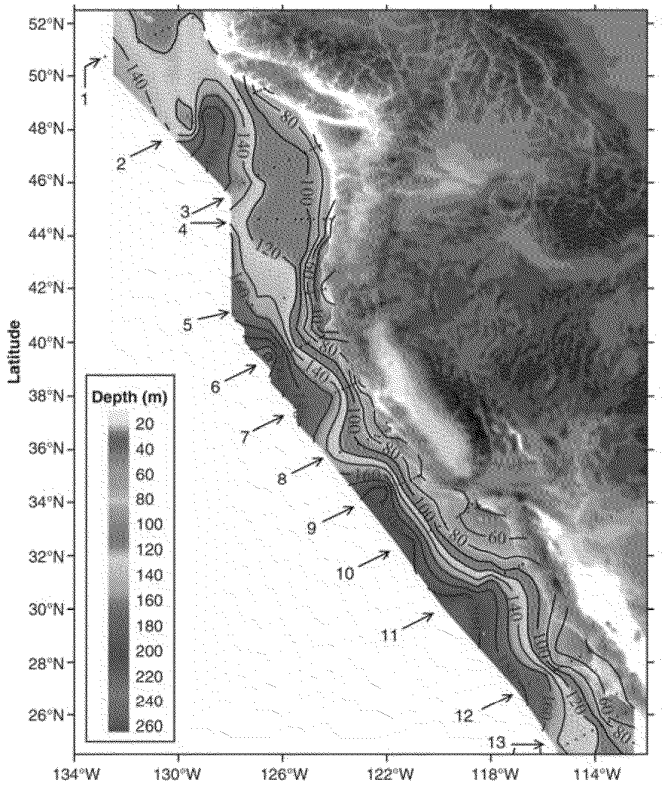

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the 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).

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.

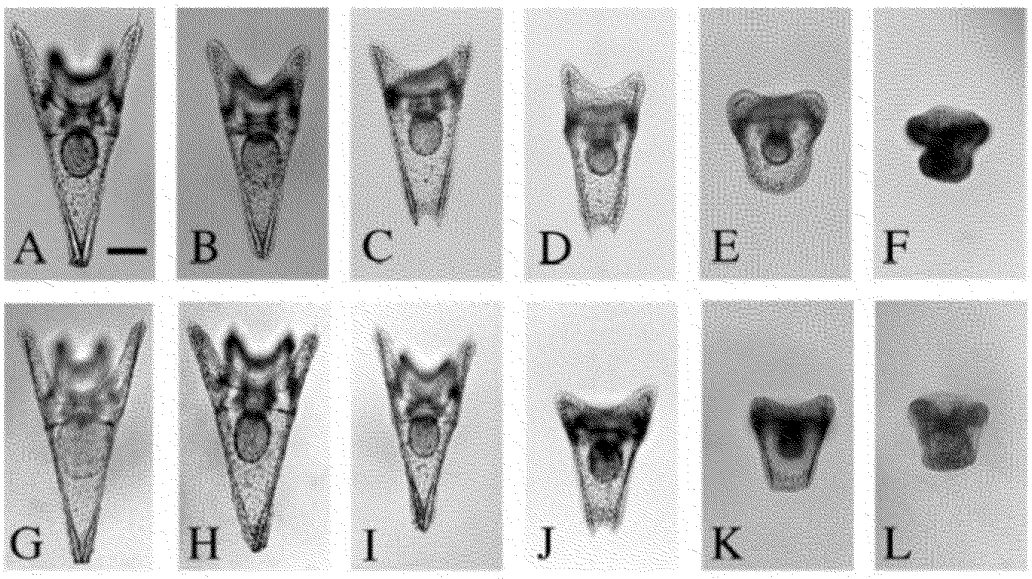

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8).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

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.

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).

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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June 30, 2015

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Re: Supplement to the Petition for Rulemaking Pursuant to section 21 of the Toxic Substances Control Act, 15 U.S.C. 2620, Concerning the Regulation of Carbon Dioxide

Dear Administrator McCarthy,

On June 30, 2015, the Environmental Protection Agency (EPA) received a petition to regulate carbon dioxide (CO_2) from cradle to grave under section 6 of the Toxic Substances Control Act (TSCA) or in the alternative to develop a testing rule for CO_2. The petition provides information concerning the devastating risk to the marine environment and wildlife, and risk to human health from ocean acidification. Accordingly, EPA must make a determination as to whether CO_2 presents or may present an unreasonable risk of injury to the environment or human health due to the severe environmental consequences of ocean acidification. As a cosigner of that petition, I submit this supplement to the petition under my signature.

US EPA section 21 guidance states: "The key findings relating to unreasonable risk must be made both when a new regulation is proposed, and when an existing regulation is amended or repealed. Petitioners should provide data to support these finds." This supplement provides additional information supporting the unreasonable risk find. I respectfully request that EPA consider the data and information provided in this supplement to the petition in making its determination on our petition.

Petitioners demonstrated that the acidification of the open ocean has a single cause but multiple effects. That the decreasing ocean pH is being inexorably driven by the increase in the atmospheric concentration of carbon dioxide from anthropogenic emissions and is the incontrovertible result of the second law of thermodynamics. That this physical and chemical dynamic has been observed, monitored, documented, and is straightforward to predict into the future. [1] That it has many harmful effects on the ecology of the ocean, some of the harmful effects are well established, others lack conclusive information or are more speculative. Many of these are significant

[1]Caldeira and Wickett, Nature 425, 2003 and Journal of Geophysical Research 110, 2005; Orr et al. 2005 Nature 437; Raven et al. 2005 ,The Royal Society.

effects, and some could be catastrophic. That these harmful effects are exacerbated in near shore areas by NOx and SOx emissions, runoff, temperature rise and other effects.[2]

Climate Impacts

According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013). So any abatement will by necessity also abate Climate change disamenities.

Under TSCA the reasonableness of the risk depends on whether the costs of the ecological and health disamenities outweigh the benefits from mitigation, minus the costs of mitigation. To the extent possible the costs and benefits must be quantified to make this determination. According to USEPA Benefit Assessment Guidelines action to mitigate ocean acidification would be classified as a "significant regulatory action" ...the ... " economic analysis of regulatory or policy options should present all identifiable costs and benefits that are incremental to the regulation or policy under consideration. These should include directly intended effects and associated costs, as well as ancillary (or co-) benefits and costs."

In EPA regulations, ancillary benefits can be much larger than direct benefits. (For example, Agency regulations to control NOx emissions are premised on the enormous ancillary particulate matter and ozone reduction benefits that result indirectly from the NOx reduction and control). This is also the case for ocean acidification (Although ocean acidification mitigation has enormous human health and environmental benefits in it's own right). Mitigation options for ocean acidification have by necessity the ancillary effect of slowing global temperature rise and preventing the disamenities associated with a global rise in temperature. Therefore this supplement presents both ocean acidification and climate information relevant to the reasonable risk finding.

Mitigation Under TSCA Includes Sequestration of Legacy Carbon

While current emissions may be the immediate cause of the increase in ocean acidification, past emissions are the proximate cause. The oceans have absorbed from about a third of the 500 plus billion tons of past or legacy carbon emissions, lessening Climate impact. However, these emissions have eroded, i.e., "used up" the buffering capacity of the oceans. This buffering capacity is what keeps ocean pH in a narrow, bio-friendly range. As the buffering capacity lessens, smaller and smaller amounts of CO_2 will result in larger and larger decreases in pH. The absorption by the ocean of legacy emissions over the past decades have caused the rapid current decrease in pH and have made the projected future decrease in pH to carbonate unsaturation levels possible, and have caused it to accelerate. Since legacy emissions are the proximate cause of both the current level and the acceleration in the decrease in pH, these emissions must be part of the design and funding of any remedy, or an undue burden is placed on the current emitters to remedy the damage caused by past emitters. The courts have held, e.g., in CERCLA cases that requirements stemming from past actions (which were legal at the time) isn't retroactive, but rather a reimbursement obligation.[3]

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[2]Duarte et al. Coastal and Estuarine Research Federation 2013
[3] UNITED STATES v. MONSANTO COMPANY, 858 F.2d 160 (4th Cir. 1988)

Again, the oceans absorb about a third of the anthropogenic emissions. This means that for decades rent seekers have extracted the benefits of fossil energy without paying for the environmental damages of the carbon emission, including the loss of the buffering capacity of the ocean and the attendant damages from ocean acidification. This is a classic "tragedy of the commons" situation. EPA has a long standing tradition and policy of making the polluter pay for environmental injury. Petitioner asks that both legacy and current emissions be included in determining the remedies and who must comply, based on the contributory proportion to the harm from ocean acidification, using, for example, the Emission Inventory. (The Agency has the authority to ignore small emitters when transactional costs of including them are too large)

CO_2 Poses an Unreasonable Risk to Human Health

Petitioner asks the Agency to consider not only the well documented health effects from climate change[4] discussed in the petition but also the direct health impact from ocean acidification. Some of these are very significant and can be quantified.

The body of the petition cites increased mortality and morbidity from loss of fisheries and declines in marine based diets. These human health effects are in addition to the increased toxicity of algal blooms mentioned in the body of the petition, which can cause paralytic shellfish poisoning in humans. The loss of fisheries from ocean acidification, and the resultant scarcity of seafood also has significant human health impacts. For example, in a Harvard School of Public Health comprehensive analysis of fish and health, combining the evidence for major health effects of omega-3 fatty acids, while accounting for the health risks of mercury, and health risks of PCBs and dioxins in both adults and infants/ young children: results show that the benefits of eating a modest amount of fish per week--about 3 ounces of farmed salmon or 6 ounces of mackerel--reduced the risk of death from coronary heart disease (CHD) by 36%. By combining results of randomized clinical trials, the investigators also demonstrated that intake of fish or fish oil reduces total mortality--deaths from any causes--by 17%. [5]

USEPA consumption surveys find that about 10% of the US population consumes at least enough fish to garner the benefit.[6] Depending on price elasticity of demand this could translate into up to half a million premature deaths/year from loss of fisheries and the resultant scarcity of seafood.[7] In addition, increase in seafood prices will result in a loss of consumer surplus. Petitioner asks that the Agency develop a deterministic or a probabilistic assessment to quantify mortality and morbidity from the decreased availability and consumption of seafood that would result from ocean acidification fishery damage, as mentioned in the body of the petition (e.g., effects on salmon from plankton impacts). This will help the risk assessment to capture this significant human health impact as required in EPA's Benefit Assessment Guidelines.

There are also indirect effects and economic consequences, which after consideration of the effect on the national economy, small business, technological innovation, the environment, and

[4] National Climate Assessment, U.S. Global Change Research Program, 2014
[5] JAMA. 2006;296(15):1885-1899;]
[6] Estimated Per Capita Fish Consumption in the United States, USEPA August 2002
[7] Am J Public Health. 2010 February; 100(2): 216–222

public health as required under TSCA, are reasonably ascertainable.[8] These include other effects on Fisheries. It is probable that wild catch seafood loss, at least in part, will be replaced by aquaculture (currently about half of the world's seafood is farmed[9]). Farmed fish are fed fishmeal, soy and grain. It has been well established that fisheries have and will be increasingly negatively affected by ocean acidification. This will cause scarcities of fishmeal, both driving up the price of farmed fish (and negatively affecting consumption) and causing more reliance on grain and soy.

The substitution of grain and soy for fishmeal, and the additional amounts of grain and soy needed for the increased farmed fish to replace the decreasing availability of wild catch may itself result in increased cost and, in some cases substitution may not be not possible due to grain and soy yield limitations. A recent Nature Communication article [10] shows robust evidence of yield plateaus due to biophysical limitations for rice, wheat and maize, which together account for ~85% of global cereal production and contribute a majority of human calories eaten directly as staple foods, or indirectly through consumption of livestock fed with grain. Seafood accounts for about 15% of the global dietary protein from animal sources. Both farmed seafood and livestock will be stressed by the plateauing grain yields.

Aside from increasing demand, grain costs will also increase due to greater input requirements[11] as marginal lands are brought into production to keep up with the increased demand. This demand and cost increase will be exacerbated by population growth, currently changing global increases in dietary animal protein, and increased labor costs from the fine tuning of many different facets of management in the production system required to increase or maintain yields.

Another factor to be considered is the dietary exposure effect of using increased soy and grain for aquaculture. The Food Quality Protection Act (FQPA) requires EPA to assess the cumulative risks of pesticides that share a common mechanism when developing tolerances. EPA has issued guidance relative to assessing that risk.[12] [13] Pesticides with common mechanisms (organophosphates (OPs), N-methy carbamates, triazines, chloroacetanides, pyrethrins/pyrethroids) all have grain and soy tolerances. This will change cumulative exposure, and under FQPA requirements EPA must reassess tolerances if these exposure pathways become larger contributors. Additionally, the metabolic pathways for the degradation products will have to be determined if they are different for aquatic species.

Petitioner requests EPA address this through its FIFRA information gathering authority and tolerance reassessment program, or explain why it's not necessary to do so. Petitioner asks that the additional exposure and risk be shared with the public if tolerances are maintained at current levels, and that these risks to human health be included in the benefits assessment. If tolerances are

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[8] TSCA section 6(c) 4
[9] State of the World Fisheries and Aquaculture, FAO, 2010
[10] Nature Communications 4, Article number: 2918 doi:10.1038
[11] CGIAR Research Priorities for Marginal Lands. FAO 1997
[12] General Principles For Performing Aggregate Exposure And Risk Assessments USEPA, 2001
[13] Guidance on Cumulative Risk Assessment of Pesticide Chemicals That Have a Common Mechanism of Toxicity. Office of Pesticide Programs, USEPA 2002

lowered, petitioner asks that any costs to growers or loss of consumer surplus be also included in the assessment.

As FQPA requires local effects be considered, USEPA should consider whether farm location relative to runoff of these pesticides need be considered in the assessment, perhaps using the monitoring protocols and mathematical models that OPP typically relies on to generate exposure estimates for water quality assessments. As more of the US population become locovores[14], local fish farming and local crops may expose special populations to increased cumulative risk.

Executive Order 12898 requires that "each Federal agency shall make achieving environmental justice part of its mission by identifying and addressing, as appropriate, disproportionately high and adverse human health or environmental effects of its programs, policies, and activities on minority populations and low-income populations". EPA's Framework for Human Health Risk Assessment to Inform Decision Making[15] recommends including social considerations and environmental justice in informing decisions on risk. In addition, under either NEPA's (National Environmental Policy Act) guidance or TSCA's "functional equivalence"[16] the analyses should consider the effects on a community by addressing the full range of consequences of a proposed action as well as other environmental stresses which may be affecting the community, including diets, or differential patterns of consumption of natural resources, which may suggest increased exposures to environmental pathways presenting potential health risk. To comply with these goals petitioner asks that EPA consider the Environmental Justice implications of whether the increased cost of seafood high in omega-3's will result in a more unhealthy ratio of omega-3 to omega-6 oils in certain low income communities. This ratio has been shown to be an important driver in mortality and morbidity studies.

Petitioner asks that the Agency consider the net effect on diet from ocean acidification and include the expected morbidity and mortality from all the changes in diet described above.

Market Failure

Petitioner endorses the President's Counsel of Economic Advisors' statement that "The emission of greenhouse gases such as carbon dioxide (CO_2) harms others in a way that is not reflected in the price of carbon-based, energy, i.e., CO_2 emissions create a negative externality. Because the price of carbon-based, energy does not reflect the full cost or economic damages, of CO_2 emissions, market forces result in a level of CO_2 emissions that is too high. Because of this market failure, public policies are needed to reduce CO_2 emissions and thereby limit the damage to economies and the natural world from further climate change."[17] One of these "harms" is Ocean Acidification. The petition and the options presented herein provide vehicles for implementing the public policy called for by the Counsel necessary to rectify the market failure.

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[14] R.E. Galt Counting and Mapping Community Supported Agriculture, ACME: An International E-Journal for Critical Geographies, 2011, 10 (2), 131 - 162

[15] Framework for Human Health Risk Assessment to Inform Decision Making, April 5, 2014, U.S. Environmental Protection Agency

[16] 489 F.2d 1247 (D.C. Cir. 1973).

[17] The Cost of Delaying Action to Stem Climate Change, CEA, July 2014.

Emission Reduction *and* Sequestration

Given the magnitude of the ocean acidification problem, the mitigation prescription to address this market failure must also be large. Nature maintains carbon dioxide atmospheric concentrations within a narrow band, by balancing emissions with sequestration. Nature efficiently removes atmospheric carbon by transforming it into biomass and minerals, or "storing" it in the oceans (the source of the ocean acidification problem). Unlike the natural cycle which is in dynamic equilibrium, the anthropogenic carbon cycle is not in equilibrium and is unbalanced. Man takes Gigatons of fossil carbon and puts it in the air, but takes very little back. In excess of a third of this increase in atmospheric carbon ends up in the ocean and lowers the ocean pH. The economics of the anthropogenic carbon cycle don't take in account the externalities of ocean acidification (or climate change) so the economic carbon cycle is skewed towards emissions and away from sequestration. While the amount of the imbalance is relatively small when compared to the annual amount of carbon nature moves into and out of the atmosphere, it is consistently biased in one direction and over the years has almost doubled the baseline atmospheric carbon.

While the Administration has not directly attempted to regulate ocean acidification it has attempted to reduce carbon emissions because of Climate considerations. The Administration's recent Climate Initiative and in fact, almost all of USEPA's climate and carbon initiatives to date, are and have focused on reducing emissions. Almost none of the efforts focus on sequestering carbon. Petitioner stresses that the carbon cycle can't presently be balanced by reducing emissions only, since, in the foreseeable future, there will continue to be a large net bias towards carbon emissions over carbon removal stemming from increasing energy demand, as well as wealth and population effects and the fossil fuel requirements of the extant energy infrastructure. (Petitioner observes that if you can't turn a sink faucet off, then you must open the drain to avoid an overflow…our energy infrastructure is a "faucet" and sequestration can be the "drain")

This is a market failure, because the environmental cost of emissions is not included in the price of energy, and therefore the environmental benefit of sequestration is not valued. Petitioner recommends that the Agency include options in the cost analysis that can significantly affect this bias, i.e., options which sequester carbon as well as options which reduce emissions. In any case, in order to determine if a risk is unreasonable under TSCA, the Agency must determine the efficacy, efficiency and supply function of all significant mitigation remedies.

Remedies

Determining whether a risk is unreasonable under TSCA is a function of government. However, as the Agency's Petition Guidance points out, petitioners have an obligation to present as much information as possible, e.g, to identify relevant aspects of the unreasonable risk determination and demonstrate that these aspects are knowable. Petitioner believes the Agency is both knowledgeable and active concerning carbon emission reduction, but less well versed and less active in sequestration. It's beyond the petitioner's responsibility and ability to provide an exhaustive, quantitative list of sequestration options. Rather examples are provided herein to demonstrate that sequestration opportunities to offset both legacy carbon and current emissions exist. The list is limited and not meant to be definitive of sequestration opportunities.

TSCA requires that the Agency consider "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" (emphasis added). [18] Some of the sequestration opportunities mentioned below are currently being employed, others are in small demonstration or pilot stages and may require additional technological innovation to become economically competitive. (Irrespective of their current status all rely on the same chemical, physical or biological mechanisms / processes that nature uses effectively to sequester large volumes of carbon.)

There is considerable literature on the ability of both Market Pull policies or Technology Push policies to increase the rate of innovation.[19]. While not all of these sequestration technologies/methods are available at the current time to provide significant mitigation, they could be in the near future given the proper market. In any case, the Agency has a successful history of setting regulatory "reach" targets (e.g., CAFE standards).

If information on the efficacy of sequestration technologies is inadequate to determine if the risk is unreasonable, Petitioner asks that the Agency use TSCA Section 4 to remedy the inadequacy. The Agency has in the past required TSCA test rules for many chemicals already released and in the environment in high volumes (such as dyes, plasticizers, flame retardants) to determine if treatment/mitigation methods (for example aerobic digestion) are sufficient to reduce the risk to human health and the environment to a reasonable level. Petitioner asks the Agency to assess the information available on the efficiency and cost of sequestration technology and methods to treat/mitigate released CO_2 to determine the adequacy of data for the purpose of a robust unreasonable risk determination. Petition asks that the Agency by rule require that testing be conducted to address any inadequacy.

Petitioner suggests costs for testing (and for remedies under sections 6 or 9, vide infra) be apportioned among CO_2 emission contributors according to the cumulative CO_2 emission inventory information the Agency has collected. This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program (a more complex format than for a single chemical, i.e., CO_2, it covered thousands of chemicals and thousands of tests from both foreign and domestic sources). [20]

Since any carbon emissions that result from sequestration actions must be subtracted to calculate net carbon sequestration, the Agency should in particular examine options that rely (completely or substantially) on alternative energy, such as biosequestration relying on solar power. Nature removes an order of magnitude more carbon out of the atmosphere every year using natural processes. By increasing the process area, volume, or efficiency of these naturally occurring processes gigatons of carbon can be sequestered. For example, grass pastures can build soil carbon slowly through microbial processes. Legume-based pastures that fix N and drive higher biomass

[18] TSCA section 6a (4)
[19] "Impact of Renewable Energy Policy and Use on Innovation"A Literature Review, Felix Groba and Barbara Breitschopf 2013, Deutsches Institut für Wirtschaftsforschung
[20] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm

production of associated grasses, drive a more rapid carbon accretion.[21] Marginal lands can be managed to trap a ton of carbon per hectare a year to equilibrium with proper management. Enhanced soil carbon is beneficial not only from it's increased productivity but also because it enables greater infiltration and retention of rainfall and this compensates for expected increases in temperature and more uncertain rainfall. In the oceans, microalgae can be fertilized sequestering carbon and then removed- harvested for products. For example the nutritional value of micro algae[22], and it's potential as a biodiesel source[23] have been extensively researched. Including ancillary benefits like these with the net sequestration benefit will provide a more complete analysis.

Recently, the World Bank investigated the capacity of different agricultural land use management practices to sequester carbon. Biomass, and especially it's soils, sequester carbon out of the atmosphere and this role as a carbon sink and as a carbon store can be strategically optimized through proven farming techniques and methods that simultaneously reduce emissions. These technical elements of climate-smart agriculture are well understood, and in addition to their technical feasibility, they can be highly productive and profitable. In the Report they estimate a enormous capacity of agriculture to sequester carbon and in turn provide marketable carbon offsets. Looking at different scenarios, that are based on different levels of international integration and ecological concern, the employment of land use and management techniques in Asia, Africa and Latin America could sequester between 12 and 18 Gt of carbon, with net positive welfare benefits, of between 1.4 and 1.6 trillion dollars by 2030. [24]

More aggressively, it has been proposed that lignin rich crops, which sequester carbon refractorially, might be used directly as a soil amendment to enrich and provide carbon to desertified or otherwise depleted lands, enabling the growth of more lignin crops to produce additional fertile soils, geometrically magnifying the sequestration.[25] Climate change may worsen desertification because of temporal changes in radiation, wind, temperature, rainfall and other parameters driven by the increased energy in the atmosphere[26]. Another economically beneficial use for tree, litter and other forestry and agricultural high lignin sources (>15%) would be for erosion control necessitated by the expected increase in rainfall in many areas from the rising temperatures.[27]

Sustainable biocharring has both an energy and a sequestration component. biocharring can be used to produce fuels and the char itself can be used to increase soil fertility and NPP, enabling sequestering more carbon. Researchers estimate that up to 12% of anthropogenic emissions can be offset by biochar. [28]

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[21] Dalal, RC, Strong, WM, Weston, EJ, Cooper, JE, Lehane, KJ, King, AJ, Chicken, CJ (1995). Australian Journal of Experimental Agriculture, **35**
[22] FAO Fisheries Technical Paper 361
[23] NREL/TP-580-24190
[24] Carbon Sequestration in Agricultural Soils, The World Bank, REPORT NO. 67395-GLB, 2012
[25]pp 150-168, Viviani, Bioenergy and Biobased Products, DOE National Bioenergy Center Strategic Partnerships Workshop April 11-12, 2001 Colorado
[26] World Meterological Oraganization, Climate_Change Desertification, 2007.
[27]Trees, Crops, and Soil Fertility: Concepts and Research Methods edited by G. Schroth, Fergus L. Sinclair
[28] Nature Communications 1: 56 doi:10.1038/ncomms1053

Reforestation and reducing deforestation can also play enormous roles and most importantly, they provide a relatively straightforward remedy that can be paid for directly by those found responsible under TSCA for the legacy carbon in the oceans. Reforestation to combat desertification is underway in Mongolia by the Mongolian government and South Korean[29]

Additionally, "blue" or coastal carbon can also play a very significant role. NOAA is encouraging the conservation of these coastal sinks and points out that current studies suggest that mangroves and coastal wetlands annually sequester carbon at a rate two to four times greater than mature tropical forests and store three to five times more carbon per equivalent area than tropical forests.[30] Most coastal blue carbon is stored in the soil, not in above-ground plant materials (biomass), as is the case with tropical forests.

The Agency should also examine options which produce (and net) carbonates from carbon dioxide[31], especially those producing salable products, such as carbon mineralization processes making carbonate building materials from carbon dioxide, e.g., green bricks and green cement, and can net energy. Building materials comprise an enormous market, as there are about 30 billion tons of concrete produced and used each year alone. Concrete accounts for about 7% of global carbon emissions. Sequestering CO_2 into green cement provides multiple opportunities and benefits: potential increases in concrete's strength, reductions in emissions, carbon sequestration, and provides significant opportunities for offset purchase.

The use of timber in high rises (to 40 stories or some cases more) to replace some of the concrete and steel can also reduce the carbon footprint of construction drastically (as both concrete and steel are carbon intensive) and can sequester atmospheric carbon at the same time. A cubic meter of wood substituted for other construction material can result in savings of 0.75 to 1 ton of CO_2.[32] This can reduce the carbon footprint of buildings by two thirds.

Practice and performance based economic incentives could be used to encourage sequestration in the building and forestry/agricultural sectors. Banked credits could be sold to offset any added cost from the differing practices/products. In the US, government construction accounts for about a quarter of new projects. These projects could account for significant sequestration if additional green construction were required to be incorporated in design. In government directed economies it could be higher.

3D printers, which can and do use biological materials (containing carbon harvested from the atmosphere) as substrates can produce myriad consumer products. This is particularly helpful because increased consumer expenditures and economic growth is almost always associated with increased energy/resource use and drive carbon emissions. In this case consumer purchases can

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[29] Min-Kyung Kang et al, Jour. Korean For. Soc. Vol. 99 No. 5, pp 655-663 (2010)
[30] http://www.habitat.noaa.gov/coastalbluecarbon.html
[31] Annu Rev Chem Biomol Eng. 2013;4:103-17. doi: 10.1146/annurev-chembioeng-062011-080951. Epub 2013 Feb 28.
[32] International Institute for Environment and Development, Using Wood Products to Mitigate Climate Change, 2004

actually reduce net atmospheric carbon. Other research demonstrates direct storage of CO2 into nonbiological compounds which can also be accessed to make consumer products[33]

These sort of options help bring the economic carbon cycle more into balance, providing value by removing carbon from the atmosphere. CO_2 not only becomes an essentially limitless resource, which can be both reduced or oxidized to produce products and/or energy, it also couples sequestration with population and economic growth.

The Agency, through TSCA section 9's access to other Federal programs, could use economic incentives to foster growth of some these options by the general population. For example, DOE and EPA's Energy Star program has prevented 1.8 billion tons of GHG emissions, by providing information that helps consumers select energy efficient devices. A similar program could be established that provides information about the net amount of atmospheric carbon sequestered in products.

Providing information to consumers concerned about ocean acidification (and climate change) enables them take direct action to mitigate these problems, and also provides a marketing incentive to companies to develop and sell these products. There is already a trend in the US for development of biocarbon products substituting for petroleum or mineral based products. Examples range from large volume products, such as home foam insulation based on soy, to smaller niche products, such as wetsuits made using biorubber rather than petroleum based neoprene (Patagonia).

As mentioned above, Nature cycles atmospheric carbon primarily by storing it in the ocean, reducing it into biological materials and oxidizing it into minerals. This latter process also provides sequestration opportunities. The IPCC [34]estimates that magnesium and calcium silicate deposits are sufficient to fix all the CO_2 that could be produced from the production of all fossil fuels resources. There have been demonstration and pilot projects that have sequestered carbon at a costs ranging from $50 to $300/ ton.[35] Some of these processes also have the advantages of yielding salable product. For example olivine has been used as an amendment to replenishing beach sand, and the weathering of the sand from the ocean waves has the potential to raise the pH of the waters.[36]

There are high volume industrial waste materials, such as 'red mud' from aluminum production[37] as well as steel and blast furnace slag, fly ash and waste concrete that can sequester atmospheric carbon, and in some cases produce salable products[38]

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[33] CO_2 Coordination by Inorganic Polyoxoanion in Water, Guanggang Gao et al, JACS communications, 2008

[34]IPCC Special Report Carbon Dioxide Capture and Storage, 2005

[35]Chem. Soc. Rev., 2014, 43, 8049

[36]International Journal of Greenhouse Gas Control 4 (2010) 855–856

[37]Peterson et al. Science of The Total Environment Volume 338, Issue 3, 15 February 2005

[38] Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard USEPA, February 2014

IntraAgency Coordination

Petitioner is aware that the Agency has operated cross-Agency programs, i.e., initiatives that all media program and other offices are required to participate in. Examples include, P2 Pollution Prevention, the IntraAgency Integration Program and the Priority Pollutant Program, all of which required coordination to achieve an environmental goal(s). Almost every Agency action, initiative, grant, etc. has carbon implications. Petitioner asserts that Ocean Acidification is, at the very least, on a par with the problem these programs were designed to address. If this is not already being done, the petitioner asks the Agency to require that all significant actions take carbon benefits explicitly into account.

The Economic Costs of CO_2 and Discount Rate

The discount rate is critical in the unreasonable risk determination, as benefit estimates depend heavily on the discount rate applied. There is debate as to applicability of current methodologies to derive these rates when applied to distant events and transgenerational effects. As Cowen and Parfit pointed out "Why should costs and benefits receive less weight, simply because they are further in the future? When the future comes, these benefits and costs will be no less real. Imagine finding out that you, having just reached your twenty-first birthday, must soon die of cancer because one evening Cleopatra wanted an extra helping of dessert".[39]. Or putting it in terms of dollars instead of baklava: Frank Partnoy, (University of San Diego) observed "A human life is often estimated to be worth around $10 million. But if you apply a three percent discount rate to this, that means that a human life five hundred years from now is only worth $3.81 today."

Further, the basis for a discount rate is the opportunity cost of taking action today to avoid future effects, i.e., the discount used must reflect the profitability of the best alternative investment opportunity. However, global warming, and even ocean acidification will have such enormous effects on agriculture, real estate, water availability, fisheries, etc, that investments in many sectors could well have limited or even negative discount rates without mitigation action. People may well be poorer in the future because of ocean acidification and climate change and have less rather than more resources to mitigate and adapt[40].

To use an ocean acidification example, an investment in ocean property in Florida could well have a negative return (if not for the owner, than for federal government which guarantees flood insurance) when the coral reefs erode and flatten (as discussed in the body of the petition) and fail to provide adequate buffer for storm surges, as could investments in commercial fisheries. Climate change effects on investment returns would be even larger. For example, the IPCC predicts a 2% net decrease in agricultural production per decade from global warming. Petitioner asks the Agency to take into account how ocean acidification and climate change will affect return on capital investment when setting a discount rate in their assessment of benefits as recommended in USEPA's Guidelines for Preparing Economic Analysis. OMB Guidance on regulatory analysis states " In some instances, if there is reason to expect that the regulation will cause resources to be reallocated away from private investment in the corporate sector, then the oppor-

[39]Tyler Cowen and Derek Parfit, Against the Social Discount Rate, in Peter Laslett and James S. Fishkin, eds, Justice Between Age Groups and Generations 144, 145 (Yale 1992).
[40] Johnson et al, Journal of Environmental Studies and Sciences September 2012, Volume 2, Issue 3, pp 205-221

tunity cost may lie outside the range of 3 to 7 percent. ” [41] The same logic must apply when it is not the regulation but the effect itself that provides an economic distortion in the absence of regulation.

Petitioner asks the Agency to consider and explain the choice of using either a Willingness to Pay (WTP), or a Willingness to Accept (WTA) in the economic valuation of benefits. This seems germane relative to the loss of oceanic buffering capacity due to past absorption by the 600 billion tons of carbon emissions from the burning of fossil fuels. Like many other effects of Ocean Acidification this loss of capacity is not presently included in the calculation of the SCC. If the Agency decides to use a Contingent Valuation Method to value the lost buffering capacity, then WTA may be appropriate as this capacity is a public good. [42]

Low Probability Catastrophic Impact Effects

Current climate cost and benefit estimates do not take into account many low probability effects with catastrophic impacts. For example, there is research to estimate probability densities for positive feedback and/or climactic tipping points, such as unstable methane deposit releases from permafrost[43], the collapse of the marine food web, impacts to cloud albedo[44], or alterations in ocean circulation[45]. These may be low probability events, but have enormous consequences. Many of these can have catastrophic Earth System effects and once they occur are essentially irreversible. Because of this, current cost and benefit estimates must be considered conservative.[46]

This is one of the reasons why the President’s Council of Economic Advisors recommended treating Climate Change prevention action as an insurance investment. Current regulations, proposed regulations, and planned regulations, do not address these severe Earth System potential impacts and do not, measurably decrease their likelihood of occurrence. Petitioner agrees with the President’s Council that Climate Change be treated as an insurance investment, and asks that the potential cost of these low probability, very high impact effects, be valued to inform the TSCA section 6 unreasonable risk decision. In lieu of a better Agency alternative, Petitioner suggests the Agency estimate the cost of an insurance premium using occurrence and impact probability of these tipping points/catastrophic events as basis, much like insurance premiums in

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[41] OMB Circular A-4

[42]Kahneman et al, Journal of Environmental Economics and Management, 22 57-70, 1992

[43]Schaefer, K., T. Zhang, L. Bruhwiler, and A. P. Barrett (2011), Amount and timing of permafrost carbon release in response to climate warming, Tellus Series B: Chem. Phys. Met., DOI: 10.1111/j.1600-0889.2011.00527.x.; oven teal, Analysis of Permafrost Thermal Dynamics and Response to Climate Change in the CMIP5 Earth System Models, JOURNAL OF CLIMATE
2013

[44] Six K.D., Kloster S., Ilyina T., Archer S.D., Zhang.K, Maier-Reimer,E., Global warming amplified by reduced sulphur fluxes as a result of ocean acidification. Nature Climate Change, doi:10.1038/nclimate1981, 2013.

[45] Rahmstorf, S., Box, J., Feulner, G., Mann, M., Robinson, A., Rutherford, S., Schaffernicht, E. (2015): Evidence for an exceptional 20th-Century slowdown in Atlantic Ocean overturning. Nature Climate Change (online) [DOI: 10.1038/nclimate2554]

[46]Weitzman, Martin L. 2009. Review of Economics and Statistics 91(1): 1-19.

the nuclear energy industry against catastrophic incidents are calculated and apply that as a surrogate for the cost of not reducing carbon emissions to mitigate ocean acidification and accompanying climate benefit.

Other Insurance Considerations

Petitioner asks that the Agency consider as a cost any direct insurance impact from Climate change: "Climate change can also adversely impact the prevalence of vector-borne diseases, food poisoning, water quality, aeroallergens, and the health of natural systems that can cause economic losses for humans, sometimes insured" "Changing weather patterns and rising ocean temperatures as a result of climate change will also likely continue to put financial stress on the National Flood Insurance Program (NFIP). Currently, the NFIP has a $19 billion deficit, and this deficit may increase each year because of $900 million in subsidies to properties that are not paying actuarially based rates. In addition, the cost to the NFIP of servicing its debt consumes much of its revenue. ... millions of Americans depend upon the NFIP for flood coverage ..."

According to Dr Evan Mills (US Department of Energy's Lawrence Berkeley National Laboratory) "there is growing acknowledgement among insurers that the impact of climate change on future insured losses is likely to be profound. The chairman of Lloyd's of London has said that climate change is the number- one issue for that massive insurance group. And Europe's largest insurer, Allianz, stated that climate change stands to increase insured losses from extreme events in an average year by 37 per cent within just a decade. Losses in a bad year could top US$1 trillion. Insurers increasingly recognise that it is the lack of action to combat climate change that is the true threat to their industry and the broader economy; engaging with the problem and mounting solutions represents not only a duty to shareholders but also a boon for economic growth.

The insurance sector thus finds itself on the front lines of climate change. The response of many, particularly in the United States, has been to focus on financial means for limiting their exposure to high-risk areas along the coastlines and areas prone to wildfires. Allstate, for instance, has said that climate change has prompted it to cancel or not renew policies in many Gulf Coast states, with recent hurricanes wiping out all of the profits it had garnered in 75 years of selling homeowners insurance. [47]The company has cut the number of homeowners' policies in Florida from 1.2 million to 400,000 with an ultimate target of no more than 100,000. The company has curtailed activity in nearly a dozen other States."

EPA Can Use TSCA to Complement Existing Federal Laws

Petitioner asks that, as required under TSCA, the Agency determine if relief is more efficient under any other Federal statute and if so, to use that authority as is required under TSCA § 9. Choosing a regulatory strategy and determining what actions are required to mitigate unreasonable risks is, again, inherently a governmental function. However, the cost and the efficiency of the mitigation options that are considered during regulatory development and assessment drive the determination of whether a risk is "unreasonable" and the array of alternatives considered need to be robust.

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[47] Conley 2007 in "Insurance in a Climate of Change: Availability & Affordability." Berkeley Lab, U.S. Department of Energy.

Because of the magnitude of Ocean Acidification risk, Petitioner believes good government demands the Agency consider a complete array of options using all authorities and tools available to efficiently address the problem. Petitioner will show that in addition to requiring relief under TSCA § 6, the Agency can use the TSCA § 9 authority to require action under either, or both, the Clean Air Act (CAA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) authorities. Relief under these statutes should also be considered in determining the cost, benefit and the most efficient remedies to mitigate the harm and risk from Ocean Acidification.

Petitioner is aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. These actions by themselves while laudable, will not stabilize atmospheric CO_2 at a level that prevents widespread harm from ocean acidification. Consider that even with a successful implementation of the Agency's planned emission reduction regulations, atmospheric concentration will pass 450 ppm around 2030, a tipping point likely to induce aragonite undersaturation in surface waters. Petitioner believes that a combination of aggressive emission reduction and sequestration is necessary to mitigate the unreasonable risk and harm caused by ocean acidification. Both CERCLA and the CAA can provide relief.

Petitioner asks that the Agency consider whether that CERCLA and/or CAA authorities present efficient opportunities for remediating ocean acidification.

1) **Remedies under the Clean Air Act (CAA)**

There are several remedies under the CAA either directly accessible or accessible under TSCA section 9. Title 42 § 7415 of the Clean Air Act addresses endangerment of public health or welfare in foreign countries from pollution emitted in United States, and directs "the Administrator, upon receipt of reports, surveys or studies from any duly constituted international agency"...to have... " reason to believe that any air pollutant or pollutants emitted in the United States cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare in a foreign country ...the Administrator shall give formal notification thereof to the Governor of the State in which such emissions originate. The notice of the Administrator shall be deemed to be a finding under section 7410 (a)(2)(H)(ii) of this title "

There have been many reports addressing the endangerment of public health or welfare from ocean acidification that have been published by duly constituted international agencies and of which the Agency is well aware and in some cases participated in. These include: the Royal Society[48]; The European Union's European Project on Ocean Acidification (EPOCA) published over a hundred scientific papers detailing the effects; the UN's Climate Change and Ocean Acidfication Synegies and opportunities within the UNFCCC, Harrould-Kolieb and Herr; and Australia's GBRMPA published Climate Change and the Great Barrier Reef: A Vulnerability Assessment in association with 85 scientific and management experts; as well as numerous IPCC Reports, in which the Agency and other Departments of the Federal Government actively participate.

[48]Royal Society (Ocean acidification due to increasing atmospheric carbon dioxide, 30 June 2005

The Columbia Journal of Law[49] describes the applicability of Section 115 to CO_2 regulation for ocean acidification mitigation, including the legislative history and how SIPs under section 7410 are mandated. The Agency's current Proposed Rule for Electric Utilities using section 7411, can serve as a template. The flexibility for State SIPs in the Rule includes by reference, their current State programs as applicable to compliance with the Rule. Some of these cited include provisions for, and allow "offsets" or carbon sequestration to be counted in reaching program goals, using for example, Cap and Trade. State by State assessment of legacy carbon could be calculated by the Agency from the Emission Inventory and these could be included in State Implementation Plans.

§ 7415 includes the requirement that a reciprocity finding that the affected foreign country gives the U.S. "essentially the same rights with respect to the prevention or control of air pollution occurring in that country as is given that country". This requirement directly addresses the often raised argument against US EPA action that posits: since Ocean Acidification has a global cause, only international action can address it successfully. Implementation of State plans would presuppose a concurrent implementation internationally. The Montreal Protocol (which found it's genesis in a TSCA action) could serve as a template for coordinating international plans for ocean acidification mitigation. The European Union's REACH (Registration, Evaluation, Authorization and Restrictions of Chemicals) regulation serves as an example of how a large attractive market (like the EU or the US) can induce foreign companies and government directed economies who wish to have continued access to the markets, to comply with environmental regulation.

Recently the US and China, which account for almost 40% of global carbon emissions, jointly announced new targets to cut emissions. Germany, Finland and other industrialized counties are also drastically cutting emissions. The foundation for a reciprocity agreement with the nations that account for most of the legacy and current emissions is already in place.

Alternatively, the CAA emission trading mechanism, which offers an often used, efficient market approach might also be accessed directly through TSCA section 9 to mitigate ocean acidification.

Under TSCA section 6: (1) A requirement ...." (B) limiting the amount of such substance or mixture which may be manufactured, processed, or distributed in commerce." ...clearly gives the Agency authority to limit current emissions, and Section 6's: "Any manufacturer or processor subject to a requirement to replace or repurchase a chemical substance or mixture may elect either to replace or repurchase the substance or mixture and shall take either such action in the manner prescribed by the Administrator." gives authority for trading options. While 'repurchase' is sequestration, "replace" is trading.

Since EPA has treated air pollutants like CO_2 as fungible in order to efficiently regulate when the "net" pollution is key, replacing carbon emitting facilities with new facilities that rely on renewable sources will reduce the net carbon in the atmosphere and thereby reduce the amount in the oceans. This would be one way for facilities to "pay down" their legacy carbon debt. The

[49]Cap-and-Trade Under The Clean Air Act?: Rethinking Section 115 , H Chang, April 2010

Agency could consider a current carbon emitting facility's development of green (e.g. solar or wind) energy capacity to *replace* (not augment) fossil energy as a legacy offset. (Assuming this is not double counting, i.e., being used to bring the facility into compliance for current emissions under another requirement). The new energy production from the no- or low- emitting source would "replace" the carbon that would be emitted from the existing energy production source, leading to a net reduction in carbon emissions. This type of offset also has the advantage of helping to build the market base for green energy and eventually lower costs for additional facilities, accelerating the needed energy infrastructure change. This is an approach the German State is pursuing through subsidies.

2) Remedies under CERCLA Under the 42 U.S. Code § 9604 Response authorities

Whenever (A) any hazardous substance is released or there is a substantial threat of such a release into the environment, or (B) there is a release or substantial threat of release into the environment of any pollutant or contaminant which may present an imminent and substantial danger to the public health or welfare, the President is authorized to act (under 42 U.S. Code § 9621), consistent with the national contingency plan, to remove or arrange for the removal of, and provide for remedial action relating to such hazardous substance, pollutant, or contaminant at any time (including its removal from any contaminated natural resource).

CO_2 can meet the CERCLA definition of "hazardous substance in in either of two ways: 1) under 9602 "The Administrator shall promulgate and revise as may be appropriate, regulations designating as hazardous substances... such elements, compounds, mixtures, solutions, and substances which, when released into the environment may present substantial danger to the public health or welfare or the environment, or, 2) by definition: "any imminently hazardous chemical substance or mixture with respect to which the Administrator has taken action pursuant to section 7 of the Toxic Substances Control Act".

If the Administrator takes action under TSCA §7 based on the imminent hazard to coral reefs and marine life, as explained in the petition, CERCLA becomes applicable[50]. While some risks to marine organisms from ocean acidification may be uncertain, many are not. Also, the risk to the coral reefs which provide protection to life and property along America's coastlines as well as significant recreational and nutritional benefits is both manifest and well documented and the risk is "imminent" within the definition of TSCA. (Alternatively, these same dangers might be used by the Administrator to directly designate CO_2 as a hazardous substance)

The imminence stems not from the point in time when the threat will be completely manifest but rather from the point in time when action must be begun to effectively mitigate or avoid the threatened effect(s). That time is now, primarily because of the enormous inertia in the carbon economic cycle. The infrastructure of energy use relies on fossil fuel combustion. There are no alternatives of sufficient capacity in the near term. To avoid reaching the point, mid to late century (given the current trajectory) where the oceans are undersaturated in carbonate and shells and coral begin dissolving wholesale, either a robust sequestration program must be developed,

[50] CERCLA section 101(14)

and/or significant energy alternatives must be made available. These are both long term programs that require decades, and must begin now.

Scientists are well **aware of the enormous risk posed by ocean acidification.** A recent study in Science found that the largest extinction event on earth was caused by ocean acidification[51]. **Dr. Jane Lubchenco, The head of the National Oceanic and Atmospheric Administration from 2008 -2013 has called ocean acidification global warming's "equally evil twin."** Unfortunately, unlike the risk from Climate Change, the magnitude of the risk to the oceans from acidification is not well known or understood by the general public. A TSCA § 7 Notice informing the public of the serious risks to coral reefs, provides the information needed to decide if changes in personal energy use, and consumption is warranted. (TSCA § 7 grants EPA authority to "require warning labels and/or instructions on containers or products". USEPA could encourage consumer choice by labeling products with large embedded carbon volume).

Changes in energy use and consumption can begin to retard the ongoing increase in atmospheric CO_2 and to lessen the effect of acidification on coral reefs. Changes in consumer choice toward less carbon intensive products could build markets for those products, making them less expensive and spurring innovation. Information on the risks can help localities plan as well. Notification of risks is one of the TSCA § 7 remedies. A TSCA § 7 Notice explaining the risks would help inform decisions concerning where to live in order to be secure in life and property, given the inevitable loss of protection to some coastal areas from extreme weather events (coincidently expected to increase with climate change) which will occur with the loss of reefs.

It also seems reasonable that, to the extent the US is harmed, it can use CERCLA to fund remedies from transboundary actors, as was the case in the Trail Smelter Arbitration.[52] Wherein the downstream Confederated Tribes of the Colville Reservation, and the State of Washington, in the US sued a Canadian smelter for dumping into the Columbia River upstream in Canada under CERCLA. This is a successful resolution of an international dispute that provided an important principle of international customary law concerning state responsibility and transboundary pollution. (Again, a TSCA § 7 action for CO_2 effect on coral reefs would define CO_2 as hazardous under CERCLA.)

Another important theory of international law is the polluter-pays principle. This theory stands for the proposition that nations should focus on internalizing environmental costs for purposes of public interest by making the polluter bear the cost of pollution. By mandating that the responsible party bear these costs, the polluter-pays principle achieves the effect of encouraging individual responsibility for environmental harm. The countries attending the Rio Convention, including the US and Canada, reaffirmed this principle in Article 16 of the 1992 Rio Declaration"[53] CERCLA's strict, joint and several liability, holds polluters responsible for damage.

The oceans have essentially been a "dump site" for CO_2 emissions, so CERCLA is a natural vehicle for seeking remedy. CERCLA has been applied to other water bodies, e.g., the upper 40 or

[51] Clarkson et al. Science 10 April 2015: Vol. 348 no. 6231 pp. 229-232
[52] United States District Court for the Eastern District of Washington, April 4, 2012
[53] Greenfield: CERCLA'S applicability abroad, Emory International Law Review;Fall2005, Vol. 19 Issue 3, p1697

so miles of the Hudson are a NPL site for pcb contamination. CERCLA is an excellent tool for seeking remedy from multiple, diverse parties, i.e., "CERCLA casts a wide net in bringing in responsible parties. Through the broad definition of hazardous substance (§101(14) - liability is extended to anything that presents an "imminent and substantial danger"), the loose interpretation of "release" (there is no time constraint on this) and the wide scope of liability (each party involved may be responsible for the entire clean up) the statute seeks to fund the clean up of these sites. Although there have been challenges to the apparently retroactive nature of this (because people are being held liable for actions that predate the statute), and as noted above, the courts have held that as the waste is continuing to cause problems, and the statute is not a punishment but rather a reimbursement obligation, the statute is not retroactive, and thus not unconstitutional. And again, small contributors can be and are routinely ignored if transaction costs are high.

Summary

Ocean acidification and its effects are complex and the state of knowledge is uneven. Depending on what USEPA knows and believes about the effects of ocean acidification there are a number of decisions that the Agency must make and actions associated with those decisions. In the introduction and in the body of the petition, petitioners ask USEPA to take several actions under TSCA § 4 and 6, and in this supplement petitioner asks the Agency to take additional appropriate actions under other federal statutes through TSCA § 9 and other TSCA authority, in order to mitigate the human health and environmental risk from ocean acidification caused by CO2 emissions.

The following describes the different paths the Agency can take in responding and what the petitioner believes the public deserves in each case. While mentioned below is the possibility of taking action under TSCA § 7, petitioner understands that § 21 cannot be used to for § 7 action, however, petitioner believes that the threat to coral reefs presented in the petition and as discussed herein make a compelling case for § 7 action.

1) EPA could decide that the current state of knowledge concerning ocean acidification is sufficient to decide that the risk(s) of ocean acidification are not unreasonable. This requires evidence that the demonstrated loss of the coral reefs, decrease in shell fish harvests, loss of competitiveness of pteropods and other organisms that secrete calcium carbonate and other ecological and health effects are known to the Agency, as are the ancillary climate benefits that occur with atmospheric carbon controls, are either outweighed by the cost of mitigation, which is also known to the Agency, or are not significant effects. In this case, petitioner asks that the Agency publish and share this information with the public.

2) EPA could decide that all or some of the information necessary to make the unreasonable risk finding is either not sufficient or not available, but this lack of data does not meet the criteria for action under TSCA § 2(b)(1) and/or TSCA § 4 . Petitioner expects in this case, an explanation of why the triggers are not met by the information presented in the petition. Since much of the risk cited in this petition come from EPA, NOAA, and other government sources, petitioner asks if USEPA has information that supersedes or discounts these conclusions, and if so to publish and share this information with the public.

3) EPA could decide that all or some of the information necessary to make the unreasonable risk finding is either not sufficient or not available, and take action under TSCA § 4. Petitioner expects in this case that the Agency will explain what information is sufficient and what is not, and develop test rules to gather information sufficient to make an unreasonable risk finding in a timely fashion.

4) EPA could decide that some of the risks from ocean acidification are unreasonable and take action under TSCA §'s 6, 9 and other statutes, but that some information is lacking for other risks and write a TSCA § 4 rule to develop the missing information. Petitioner expects in this case that the Agency will explain what information is sufficient and what is not, develop test rules to gather information sufficient to make an unreasonable risk finding for the risks that are uncertain, and take action for the risks that are unreasonable.

5) The Agency, in combination with any of the above options, could publish a TSCA § 7 Notice informing the public of the serious risks to coral reefs associated with ocean acidification, it's causes, and what must be done to mitigate it. As explained above this information is needed by the public to judge the severity of the risk, adequacy of governments response to protect human health and the environment, and what precautions, if any, are necessary to take.

6) EPA could grant the petition and propose rules to mitigate ocean acidification using TSCA, CERCLA, CAA and/or other Agency and Federal authorities as appropriate. Petitioner endorses this action.

Sincerely,

/s/ Donn J. Viviani

Donn J. Viviani PhD.

Donn J. Viviani 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 Quality 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 greatly enjoys the ocean and cosigns the petition and submits this supplement, in part, so his grandchildren will be able to enjoy it as well.

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From: Helfand, Gloria
Sent: Mon 7/27/2015 4:44:05 PM
Subject: RE: interesting papers from NBER summer workshop

For those interested in the Parry paper on co-benefits, Meredith Fowlie at Berkeley has a summary in this blogpost. It inverts the co-benefits argument we've been hearing (they shouldn't be used to justify a rule) and says that the co-benefits of climate regulation may provide enough domestic benefits in many countries to justify climate action on that basis alone.

.

http://ei.haas.berkeley.edu/

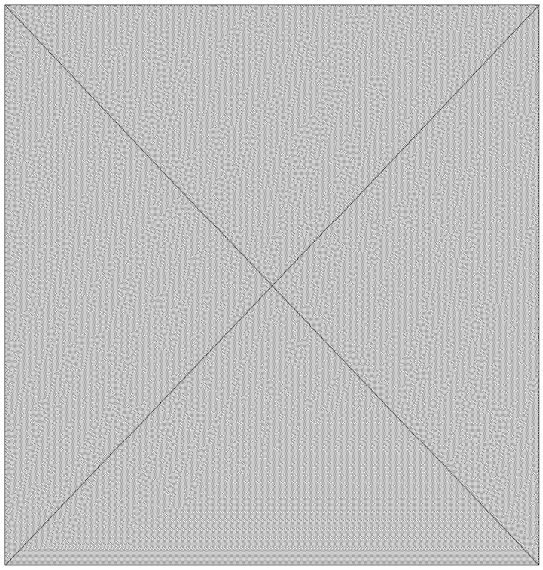
Membership has its Co-benefits

A new post by Meredith Fowlie

Concerns about local air pollution can boost support for action on global climate change

Last week marked the first "informal ministerial consultations" in the run up to the UN climate talks in December. The objective of these informal meetings before The Meeting is to provide the opportunity to find common ground and an organizing framework for what the UN Climate Chief is ominously calling the "last chance for a meaningful agreement".

Two decades worth of efforts to broker a binding global climate change treaty from the top down have largely failed. But hope springs eternal, and there is belief that a more "bottom up" approach which allows countries to define their own contributions will break the impasse. Each country has been asked to submit a self-determined national "intention" to curb its greenhouse gas emissions. These pledges will provide the foundation for any climate deal reached in Paris.



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Gloria Helfand, Ph.D.

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From: McGartland, Al
Sent: Friday, July 24, 2015 9:15 AM
To: Helfand, Gloria; DeMocker, Jim; Fawcett, Allen; Harvey, Reid; Hubbell, Bryan; Weatherhead, Darryl; Shouse, Kate
Cc: Rennert, Kevin; Wolverton, Ann; Kopits, Elizabeth; Marten, Alex; Newbold, Steve; Nagelhout, Peter
Subject: interesting papers from NBER summer workshop

Colleagues: I was lucky enough to attend the NBER summer workshop. While there were a number of interesting papers, several were particularly relevant for us.

1. The first was a randomized control trial, behavioral economics study by folks at Univ. of Chicago. They examined ways to get air line pilots to do their job in ways that would reduce fuel inefficiency (thereby lowering their ghgs). Non-Responsive

Non-Responsive

Non-Responsive Unfortunately, the paper is not yet available.

Greer K. Gosnell, London School of Economics

John List, University of Chicago and NBER

Robert Metcalfe, University of Chicago

The Behavioralist Takes Flight: Leveraging Field Experiments to Lower Carbon Emissions from Airplanes

Discussant: Justine Hastings, Brown University and NBER

2. The second paper was presented by Ian Parry – now at the IMF. Ian calculates a carbon tax in each country that would be based solely on the "co-benefits" of reduced criteria air pollutants. Hence he argues its in most countries selfish interest to reduce ghgs because they would reap the benefits of the reduced air pollution. This paper is getting traction in a number of areas. I have attached that paper.

3. The NBER workshop devoted a fair amount of time to Energy Efficiency – there were two more papers that found that low income EE programs have huge net costs.
http://conference.nber.org/confer/2015/SI2015/EEE/EEEprg.html

4. There was also a provocative presentation that suggests increased violent deaths from rising temperatures due to climate change. That paper was not available either.

Ceren Baysan, University of California at Berkeley

Marshall Burke, Stanford University

Solomon M. Hsiang, University of California at Berkeley and NBER

Edward Miguel, University of California at Berkeley and NBER

Felipe Gonzalez, University of California at Berkeley

Economic and Non-Economic Factors in Violence: Evidence from Organized Crime, Suicides and Climate in Mexico

Discussant: Matthew Kahn, University of Southern California and NBER

And for Allen Fawcett, and the SCC folks there was mathematical optimal growth model that examined the effects of catastrophic risks on optimal policy. This paper can be found at the workshop website: http://conference.nber.org/confer/2015/SI2015/EEE/EEEprg.html

Frederick van der Ploeg, University of Oxford

Aart de Zeeuw, Tilburg University

Climate Tipping and Economic Growth: Precautionary Capital and the Price of Carbon

Discussant: Billy Pizer, Duke University

To: Shouse, Kate[Shouse.Kate@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: Marten, Alex
Sent: Fri 7/24/2015 2:04:03 PM
Subject: RE: nomenclature (no action needed)

:)

--

Alex L. Marten
phone: (202) 566-2301
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From: Shouse, Kate
Sent: Friday, July 24, 2015 9:46 AM
To: Marten, Alex; Kopits, Elizabeth
Subject: nomenclature (no action needed)

One benefit of the clarified nomenclature is perhaps less time spent on this in future rulemakings:

Commenter states the terminology "social cost of carbon" is wrong and misleading. As EPA knows, greenhouse gases, including carbon dioxide, are not "Carbon". There are more greenhouse gases than carbon dioxide. Methane (natural gas) is an important greenhouse gas. The IPCC2013 Summary for Policy Makers has acknowledged that the global warming potential (GWP) of methane has been underestimated. EPA has to address the problem in all of its analyses, including the planned regulation of new and/or existing natural gas plants. This major error also needs to be addressed in the IAMs. Humans exhale carbon dioxide (CO2), not carbon.

Response 4.5-21: EPA disagrees with the commenter, who has incorrectly assumed that the common shorthand of "carbon" means that the social cost of carbon dioxide (SC-CO_2) estimates have not been adjusted to account for the mass of carbon in carbon dioxide emissions. One of the steps in the estimation of the SC-CO_2 used in this rulemaking is to translate the molecular weight of carbon to the molecular weight of carbon dioxide. Furthermore, the RIA for the

proposed rulemaking clearly defined the shorthand of "SCC" or "social cost of carbon" as accounting for the carbon in carbon dioxide emissions: "The social cost of carbon (SCC) is a metric that estimates the monetary value of impacts associated with marginal changes in CO_2 emissions in a given year" (RIA at proposal, section 5.7.1). The RIA for this rulemaking and the supporting documentation, including the social cost of carbon technical support documents, all clearly show that the units are denominated in dollars per ton CO_2 emissions. EPA is well aware that carbon dioxide is not the only greenhouse gas and that methane is an important greenhouse gas. See section III.G of the preamble to the final rulemaking for discussion about why this action regulates only emissions of CO2. See Response to Comments section 4.5, comments X through X, for EPA's response to comments on the IAMs used to estimate the SC-CO2 and the climate science components of these models.

WP/

IMF Working Paper

How Much Carbon Pricing is in Countries' Own Interests? The Critical Role of Co-Benefits

*Ian Parry, Chandara Veung, and Dirk Heine**

*Parry and Veung: Fiscal Affairs Department, IMF; Heine: University of Bologna. We are grateful to Jorge Alvarez, Tim Callen, Alfredo Cuevas, Vitor Gaspar, Michael Keen, Francisco Roch, Carlo Sdralevich, and Roman Zytek for very helpful comments and suggestions on an earlier draft.

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IMF Working Paper

Fiscal Affairs Department

How Much Carbon Pricing is in Countries' Own Interests? The Critical Role of Co-Benefits

Prepared by Ian Parry, Chandara Veung, and Dirk Heine

Authorized for distribution by Michael Keen

August 2014

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Abstract

This paper calculates, for the top twenty emitting countries, how much pricing of carbon dioxide (CO_2) emissions is in their own national interests due to domestic co-benefits (leaving aside the global climate benefits). On average, nationally efficient prices are substantial, $57.5 per ton of CO_2 (for year 2010), reflecting primarily health co-benefits from reduced air pollution at coal plants and, in some cases, reductions in automobile externalities (net of fuel taxes/subsidies). Pricing co-benefits reduces CO_2 emissions from the top twenty emitters by 13.5 percent (a 10.8 percent reduction in global emissions). However, co-benefits vary dramatically across countries (e.g., with population exposure to pollution) and differentiated pricing of CO_2 emissions therefore yields higher net benefits (by 23 percent) than uniform pricing. Importantly, the efficiency case for pricing carbon's co-benefits hinges critically on (i) weak prospects for internalizing other externalities through other pricing instruments and (ii) productive use of carbon pricing revenues.

JEL Classification Numbers: H23, Q48, Q54, Q58

Keywords: carbon pricing; co-benefits; air pollution; fuel taxes; top twenty emitters

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I. INTRODUCTION

There has been much agonizing over achieving the *collective* benefits from addressing global climate change. However, pricing carbon dioxide (CO_2) emissions from fossil fuel use can produce important *national* co-benefits. Most obviously, as carbon charges reduce use of coal, natural gas, and petroleum products, this reduces the amount of people killed by outdoor air pollution, currently estimated at 3.7 million a year worldwide.[1] To take another example, if congestion, accidents, and other externalities from motor vehicle use are not fully internalized through other pricing policies, again there are potentially significant co-benefits to the extent that carbon charges reduce vehicle use. The potential for co-benefits suggests that countries need not wait on internationally coordinated efforts if some carbon mitigation is in their own national interests—that is, the domestic environmental benefits exceed the CO_2 mitigation costs, *leaving aside climate benefits*.

These considerations raise three important questions for policy.

First, what *scale* of CO_2 pricing is in countries' own interests and how this would affect CO_2 emissions? Ideally non-CO_2 externalities would be internalized through other policies, including charges for air emissions from coal and for peak-period driving on congested roads. However, until such policies are comprehensively implemented (likely a long time given that no country presently has anything like fully corrective charges) it is entirely appropriate to price CO_2 emissions for domestic co-benefits (prior to assessing additional measures warranted by global concerns).

Second, given cross-country heterogeneity in co-benefits (and medium-run constraints on internalization of co-benefits through other policy instruments), efficiency requires differentiated carbon prices across countries, with prices higher in countries with greater co-benefits per ton of CO_2 reductions. The question is whether the extra benefits from nationally efficient carbon pricing, compared with uniform pricing (resulting, for example, from linking trading systems), are empirically large—if so, this suggests the potential superiority of pricing regimes allowing countries to choose their own emission prices (ideally subject to some agreed minimum price reflecting global climate damages) over agreements inducing all countries to price emissions at the same rate.

The third question is how much revenue is raised from nationally efficient CO_2 pricing and how revenue use might affect the net benefits from pricing co-benefits in different countries. In the latter regard, prior literature (e.g., Goulder et al. 1999, Parry et al. 1999) emphasizes the large differences in costs between carbon pricing policies where revenues are used productively—most obviously to lower the burden of income and other taxes that distort the level of economic activity and its composition—versus carbon pricing policies (like trading systems with free allowance allocations or carbon taxes with low-value earmarks) that fail to exploit efficiency gains from recycling opportunities.

[1] See WHO (2014), though not all of these deaths are due to fossil fuel emissions, and some are jointly determined with indoor air pollution.

This paper seeks to address the above three questions[2], though the main focus is on assessing *nationally efficient* CO_2 prices, that is, prices reflecting domestic (non-internalized) environmental benefits per ton of CO_2 reductions. These prices are based on country-level estimates of (non-CO_2) environmental damages by fossil fuel product from Parry et al. (2014), and a simple spreadsheet model populated with fuel use, price, and tax/subsidy data, along with simple rules of thumb for the responsiveness of fuel use to carbon pricing. Results are provided for the top twenty CO_2 emitting countries, collectively accounting for 80 percent of current, energy-related, global CO_2 emissions.

The main findings can be summarized as follows.

As regards the first question, the nationally efficient CO_2 price is typically quite large, for example, $63 per ton—estimated for year 2010 and in US $ for that year—in China, and averages $57.5 per ton among the top twenty emitters. For comparison, a US government study (US IAWG 2013) puts the global damage from CO_2 emissions at $35 per ton, and CO_2 prices in the European Union's Emissions Trading System have been below $10 per ton since January 2013. In most cases, co-benefits primarily reflect reduced air pollution deaths from less coal use, though in some cases they primarily reflect reduced road fuel subsidy distortions and reduced vehicle externalities. In a few cases (where health damages from coal are limited and motor fuel excises are broadly in line with, or exceed, non-carbon externalities) nationally efficient CO_2 prices are around $10 per ton or less, and negative in one case (Brazil, where fuel taxes currently overcharge for domestic externalities). Imposing nationally efficient CO_2 prices reduces total CO_2 emissions for the top-twenty emitters by 13.5 percent below baseline levels (a reduction in global emissions of 10.8 percent).[3]

On the second policy question, net economic benefits are increased by 23 percent under nationally efficient CO_2 prices rather than a uniform price (for the same 13.5 percent reduction in emissions from the largest twenty emitters). This is a significant (though not dramatic) gain and reinforces the pragmatic case for flexible pricing regimes when co-benefits, or more generally fiscal needs and political feasibility differ across countries, or when equity concerns (given constraints on international transfers) warrant lower prices for lower income countries.

As regards the third policy question, on average revenues are large, almost 2 percent of GDP across the top twenty countries. Moreover, if revenues from nationally efficient carbon prices are used to cut broader income taxes, the overall benefits from carbon pricing can increase substantially, on average by about 100 percent (this is the 'double dividend'

[2] A further issue, not examined here, is that international emissions offset programs become less attractive from a national perspective to the extent they reduce domestic CO_2 abatement and hence domestic co-benefits (e.g., Nemet et al. 2010).

[3] Some other studies discussed below also provide estimates of health co-benefits from reducing CO_2, though not for all the twenty countries considered here and leaving aside prior fuel taxes/subsidies and broader externalities.

which can occur when the full range of distortions from the broader fiscal system is properly considered). But if revenue recycling benefits are forgone, the costs of carbon pricing are substantially higher, and actually exceed co-benefits. This underscores the key reservation about environmental taxes, namely the risk that revenues are used for low-value purposes—combining carbon taxes with offsetting reductions in other taxes avoids this risk.

The usual caveats about parameter uncertainty apply—due to data constraints and uncertainties (e.g., over pollution/health relationships or the valuation of health effects) co-benefits may be measured with considerable imprecision, though sensitivity analyses suggest the general flavor of the results is robust (if anything, co-benefits may be significantly understated here due to conservative assumptions). Terms of trade effects, which can lower national (but not global) welfare for fuel exporters, are however excluded, as are emissions leakage issues[4], and adjustment costs from resource re-allocations across sectors. It should also be noted that that the measurement of energy subsidies used here (accounting for just over half of the nationally efficient CO_2 price in Saudi Arabia, for example) is not universally accepted, subsidies vary year-to-year with international fuel price volatility, and for practical purposes it may make more sense to reform the subsidies first, before implementing (more opaque) carbon pricing schemes.

The rest of the paper is organized as follows. Section 2 discusses a straightforward formula for the nationally efficient CO_2 price and country-level data needed to implement it. Section 3 presents the main results. Section 4 introduces broader fiscal linkages. Section 5 offers concluding remarks.

II. Defining and Measuring Nationally Efficient CO_2 Prices

A. Analytical Framework

This sub-section discusses the welfare effects of carbon pricing in the presence of fuel taxes/subsidies and environmental externalities and (very basic) formulas to be estimated.

(i) Assumptions

A very simple comparative static model of fossil fuel use in a particular country is used where X_i denotes the consumption of fuel, □ is the pre-tax supply price, and i indexes four possible fuels—coal, natural gas, gasoline, and diesel used by road vehicles.[5]

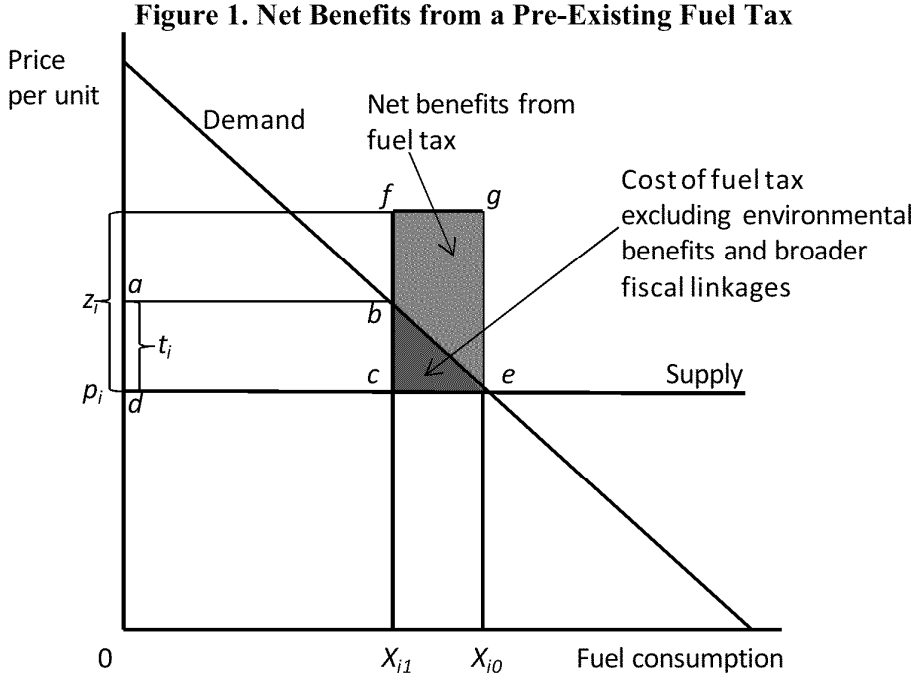
[4] Usually leakage refers to partially offsetting increases in CO_2 emissions in other countries without carbon pricing as energy-intensive, trade-exposed firms relocate away from countries with carbon pricing. More generally, some of the domestic air pollution benefits might be offset if coal production relocates to neighboring countries and the pollution crosses borders.

[5] Other fossil fuel products (e.g., diesel for farm and construction vehicles), are not included as their non-CO_2 external costs have not been consistently estimated across countries, though their inclusion in the analysis would not have a major impact on the results.

The fuel market prior to carbon pricing is shown in Figure 1. The height of the demand curve at any point is the benefit to fuel users from an extra unit of consumption (e.g., the benefit, net of travel time costs, from vehicle travel from an additional liter of gasoline), while the height of the supply curve reflects the costs (payments for labor, capital, energy, and resources to extract, transport, and process fuel, or import it) of producing an extra unit. The fuel demand curve is taken as linear over the relevant range for analytical convenience, which is a reasonable approximation given the scale of fuel reductions considered here. In addition, the fuel supply curve is taken to be perfectly elastic—allowing for an upward sloping supply curve would dampen fuel responses to carbon taxes, but perhaps only modestly in the longer run when supply curves tend to be relatively flat (e.g., Bovenberg and Goulder 2001).

Suppose there is a pre-existing excise tax of [illegible] per unit on fuel i,[6] so the consumer fuel price is [illegible] and fuel consumption is [illegible]. Compared with the zero-tax case, consumer (or fuel user) surplus is lower by trapezoid *abed*, while the government gains rectangle *abcd* in tax revenue, leaving a welfare cost of triangle [illegible] (welfare costs, correctly measured to account for linkages with the broader fiscal system, are discussed later).

Figure 1. Net Benefits from a Pre-Existing Fuel Tax



[6] t_i excludes any value added or general sales tax, as these taxes apply to consumer goods in general and therefore do not affect (to an approximation) affect the consumption of the fuel relative to other consumer products.

Suppose also that fuel use is associated with a *domestic* environmental cost (i.e., excluding CO_2 damages) per unit of z_i. For coal and natural gas these costs primarily reflect mortality risks to people exposed to the air pollution produced by combusting these fuels. For gasoline and road diesel, the costs also include those imposed on others from the extra road congestion, accident risk, and road damage due to the driving associated with additional fuel use. In measuring these externalities, account is implicitly taken of existing regulations, for example for emissions control technologies or vehicle safety, through their effects on observed emission rates, traffic fatalities, etc. Box 1 discusses further externalities from fuel use that (for various reasons) are excluded from co-benefit estimates used here, terms of trade effects, perhaps, being the most notable.

Accounting for these environmental costs, the fuel tax now produces domestic environmental benefits of rectangle *fgec* in Figure 1 and there is a net welfare gain, of trapezoid *fgeb*—a positive welfare gain is more likely the larger are non-CO_2 environmental costs per unit relative to the fuel tax.

In contrast if fuel is subsidized (which is common, for example, for petroleum in oil producing countries in the Middle East and North Africa where administered pricing causes large divergences between international and domestic prices) [illegible] 0 and there is a deadweight loss from the subsidy, the mirror image of triangle *bec* in Figure 1, between the supply and demand curve to the right of fuel consumption [illegible] In addition, there is a further deadweight loss equal to the extra consumption caused by the subsidy, times the environmental damage per unit of fuel use.

(ii) Nationally Efficient CO_2 Prices

Figure 2 shows the impact of a new carbon charge of [illegible] per ton of CO_2 emissions imposed on a fuel with non-CO_2 environmental damages and pre-existing taxes and CO_2 emissions factor (i.e., tons of emissions released per unit of fuel combustion) e_i. Trapezoid *abcd* reflects the impact of the charge on exacerbating the deadweight loss from the fuel tax but, for the case illustrated here, this is more than offset by the non-CO_2 environmental benefits, leaving a net welfare gain of trapezoid *efba*. This trapezoid has average height [illegible] 72 and its base, the reduction in fuel use, is

(1) [illegible]

In equation (1), [illegible] is a fuel price elasticity, where ~ reminds us that the tax-inclusive prices of all fuels are changing simultaneously with carbon taxes, not just the own price, and the elasticity is evaluated at [illegible] would be the same as the own price elasticity of demand if there are no cross-price effects among fuels but will be smaller in size if fossil fuels are substitutes.

Box 1. Other Externalities from Energy Use

There are a variety of other candidates for externalities associated with the production and use of fossil fuel energy that, for various reasons, are not taken into account here. Examples include:

Active living benefits from travel mode shifting. City-level studies (e.g., Woodcock et al. 2009) suggest there are substantial health benefits when individuals shift away from car trips to other travel modes involving physical exercise, including biking, walking, and walking to transit stops. However, much of the behavioral response to motor fuel taxes reflects other factors (e.g., longer run improvements in vehicle fuel economy, car pooling, combining car trips, using transit with minimal walking distance to stops) and people may internalize at least some of the health benefits in their travel mode decisions.

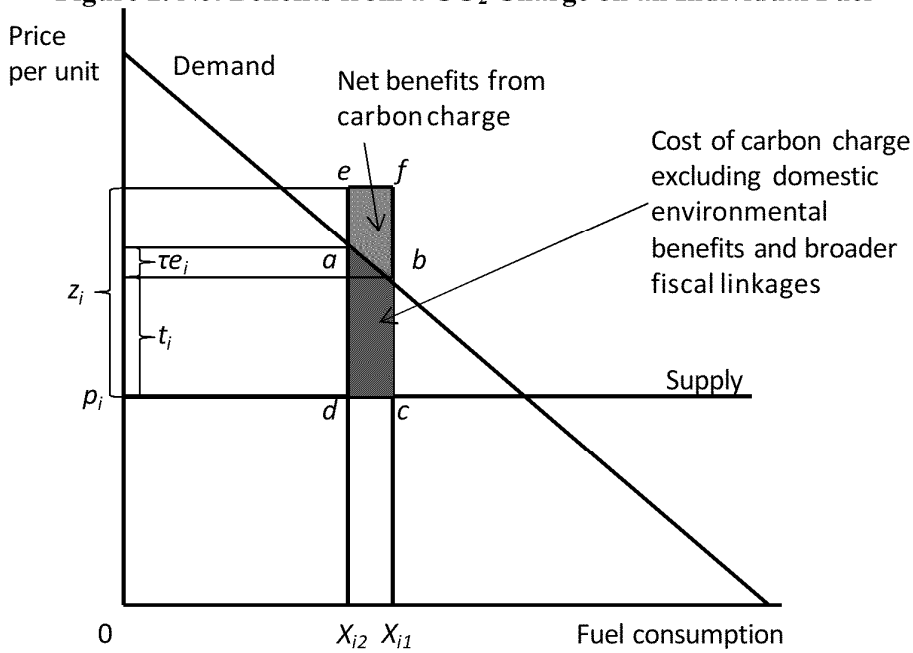
Environmental impacts from fuel extraction, storage, and transportation. Adverse side effects here include de-spoiling of the natural environment at mining and drilling sites, toxic releases from mine tailings and fuel processing wastes, leakage from fuel storage tanks, oil spills, etc. However, these types of external costs appear to be small in magnitude relative to external costs considered here (e.g., NRC 2009) and they are better addressed through other instruments than fuel taxes (e.g., double hull requirements for tankers, requirements that mined areas are returned to their natural state).

Energy security. The external costs of foreign energy dependence have always been opaque, and more so as expanding supplies of unconventional oil and gas reduce the share of global supplies coming from regions that might be viewed as unstable. In individual cases, policies to promote greater diversity in energy supply may make sense, but it is difficult to develop consistent, cross-country estimates of taxes to correct for energy security concerns.

Indoor air pollution. The World Health Organization (WHO 2014) estimates that even more people die prematurely from inhaling indoor air pollution (e.g., fumes from fuel burning in cooking stoves) than from outdoor air pollution. But again, to what extent indoor air pollution—where the households causing pollution are mostly the ones affected by it—should be viewed as an external cost is not entirely clear. Moreover, there is a risk that high prices for taxed fossil fuels may cause switching to untaxed fuels (e.g., biomass, garbage) with equally, or perhaps worse, health effects. More pressing policies might include, for example, incentives for better ventilated stoves and clean fuel alternatives.

Terms of trade effects. If a group of countries collectively price carbon emissions this can result in lower international fuel prices and a transfer from fuel exporters to fuel importers—effectively, a worsening of the terms of trade for the former. From a national welfare perspective, this would represent a co-cost rather than a co-benefit for exporters. But these costs are not considered here as they are tricky to estimate—they depend, for example, on how many countries price carbon and how fuel supply (often in administered markets) responds.

Figure 2. Net Benefits from a CO_2 Charge on an Individual Fuel



Aggregating over fuel markets (where quantity changes reflect both own- and cross-price effects), the total welfare change is:

(2) [illegible]

Differentiating (2) with respect to [illegible] (p is constant) gives the nationally efficient CO_2 tax or price:

(3) [illegible]

where [illegible] is the (initial) share of CO_2 emissions from fuel *i* in total emissions. The nationally efficient carbon tax is higher:

- the larger are the non-internalized, non-CO_2 external costs for fuels (relative to fuel prices);
- the greater the share of emissions accounted for by fuels with relatively high net external costs; and
- the greater the relative price responsiveness of fuels with relatively high net external costs.

However, a proportionate increase in all fuel price elasticities has no effect on the efficient tax—this increases the co-benefits and the CO_2 reductions in the same proportion, but with no effect on co-benefits per ton of CO_2 reduced. In other words, the efficient tax is independent of the overall responsiveness of the fossil fuel energy system to the tax (as

reflected, for example, in the prospects for renewables and adoption of energy-saving technologies).

Equations (1) to (3) are applied using data discussed below, and used (in a spreadsheet) to infer nationally-efficient carbon prices, and their impacts on emissions, fuel use, and welfare.

B. Data

This subsection discusses baseline emissions and fuel data, fossil fuel externalities, and the price responsiveness of fuel use. The focus is on the top twenty CO_2 emitting countries, henceforth "T20". The study year is 2010 (which avoids the need for data forecasting), the question asked being what would have been the nationally efficient CO_2 price for T20 countries in that year.

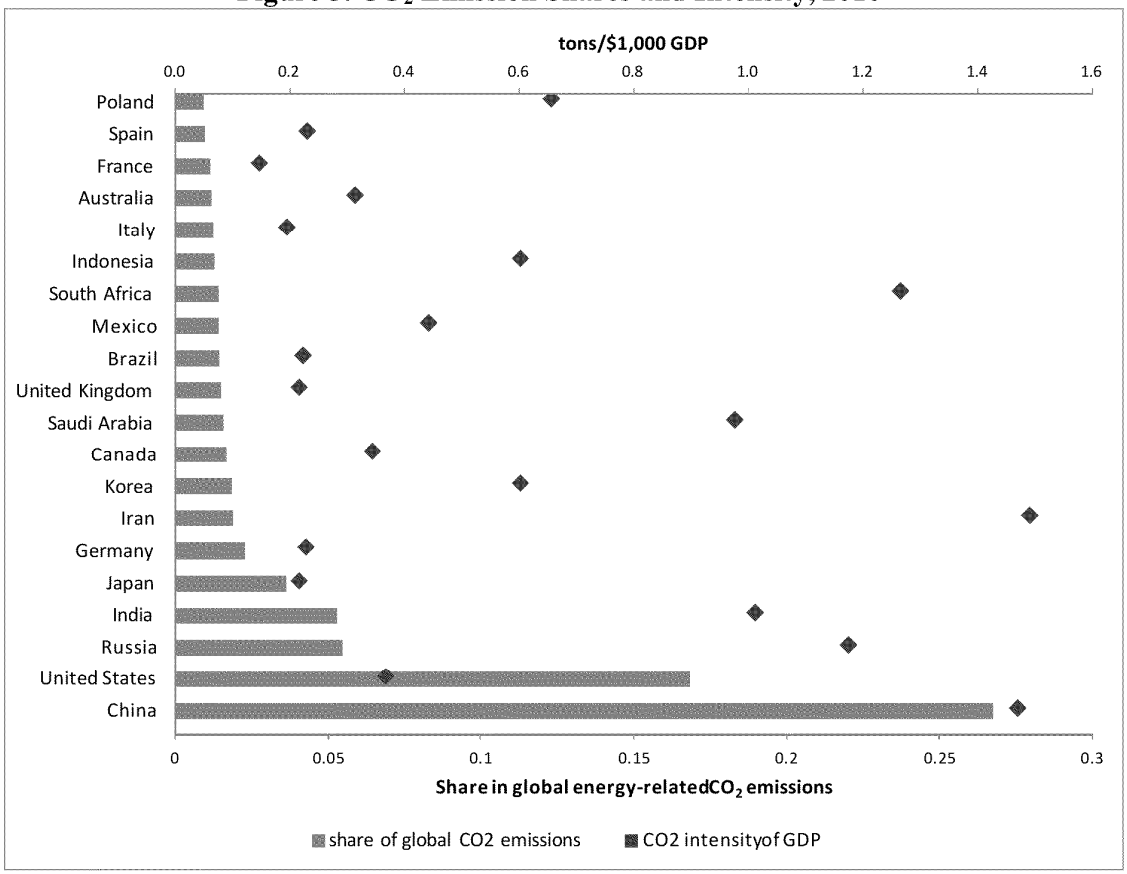
(i) Emissions and Fuel Data

Energy-related CO_2 emissions for 2010 (and GDP) are taken from IEA (2014). As indicated in Figure 3, China is the biggest emitter (26.8 percent of global emissions), followed by the United States (16.9), Russia (5.5), India (5.3), Japan (3.6), Germany (2.3) and Iran (1.9), while Poland (0.9) is the smallest emitter among the T20. The T20 together accounted for 80 percent of global energy-related CO_2 emissions in 2010.

Also shown in Figure 3 is the CO_2 intensity of the economy, measured in tons per $1,000 of GDP—for a given carbon price and proportionate emissions reduction, the CO_2 intensity indicates the scale of potential revenues and net economic benefits relative to the size of the overall economy. Most countries have a CO_2 intensity of around 0.2 to 0.6 tons per $1,000 of GDP, though China, Russia, India, and South Africa (all heavy coal users), and Iran and Saudi Arabia (intensive petroleum users), have CO_2 intensities of around 1.0 or more.

Consumption of coal, natural gas, gasoline, and motor diesel by country for 2010 was also obtained from IEA (2014).

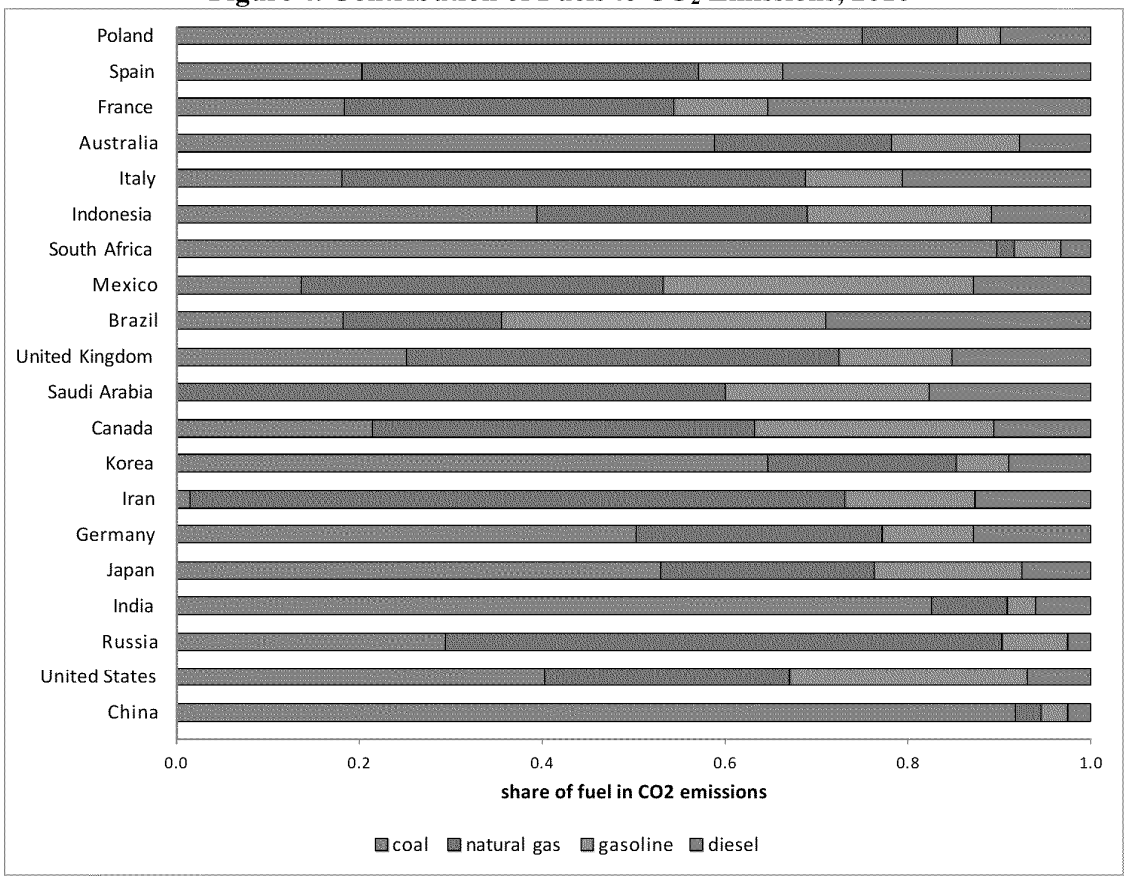
Figure 3. CO_2 Emission Shares and Intensity, 2010



Source. IEA (2014).

Figure 4 shows the individual contribution of these fuels (using their carbon emissions factors—see below) to total emissions from the four fuels. Coal accounts for 75 percent or more of emissions in China, India, Poland, and South Africa but 20 percent or less in Brazil, France, Italy, Mexico, Saudi Arabia, and Spain. Natural gas accounts for around 20 to 60 percent of emissions in 15 countries, though only 2 to 3 percent in China and South Africa. Motor fuels combined mostly account for around 10 to 50 percent of emissions.

Figure 4. Contribution of Fuels to CO_2 Emissions, 2010

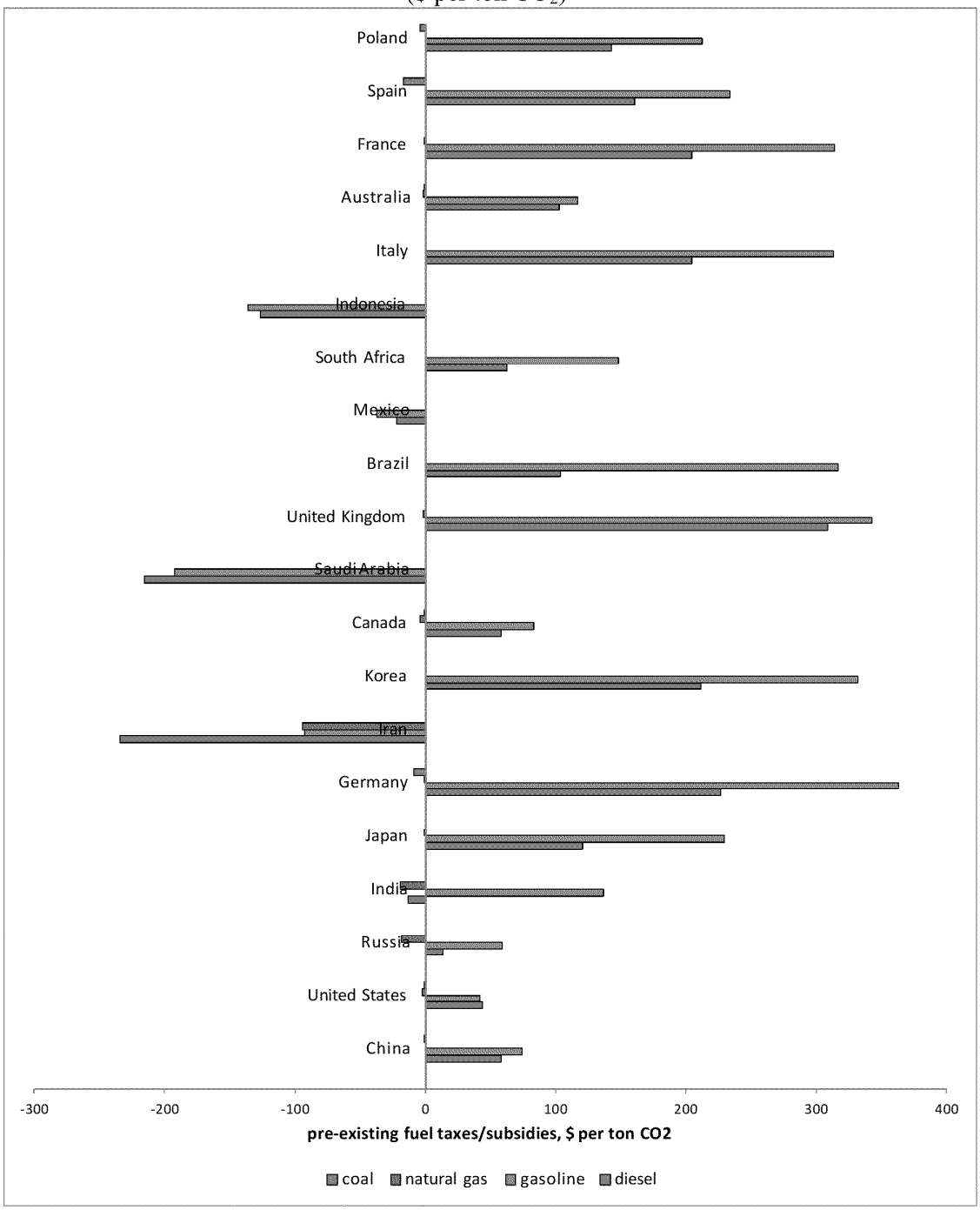


Source. IEA (2014).

Carbon emissions factors ( ) are taken from Parry et al. (2014) and show essentially no cross-country variations for a particular fuel, though per unit of energy, natural gas, gasoline, and motor diesel generate about 59 percent, 73 percent, and 78 percent respectively of the CO_2 emissions per unit of coal energy. Carbon emissions factors and fuel use give the CO_2 shares ( ).

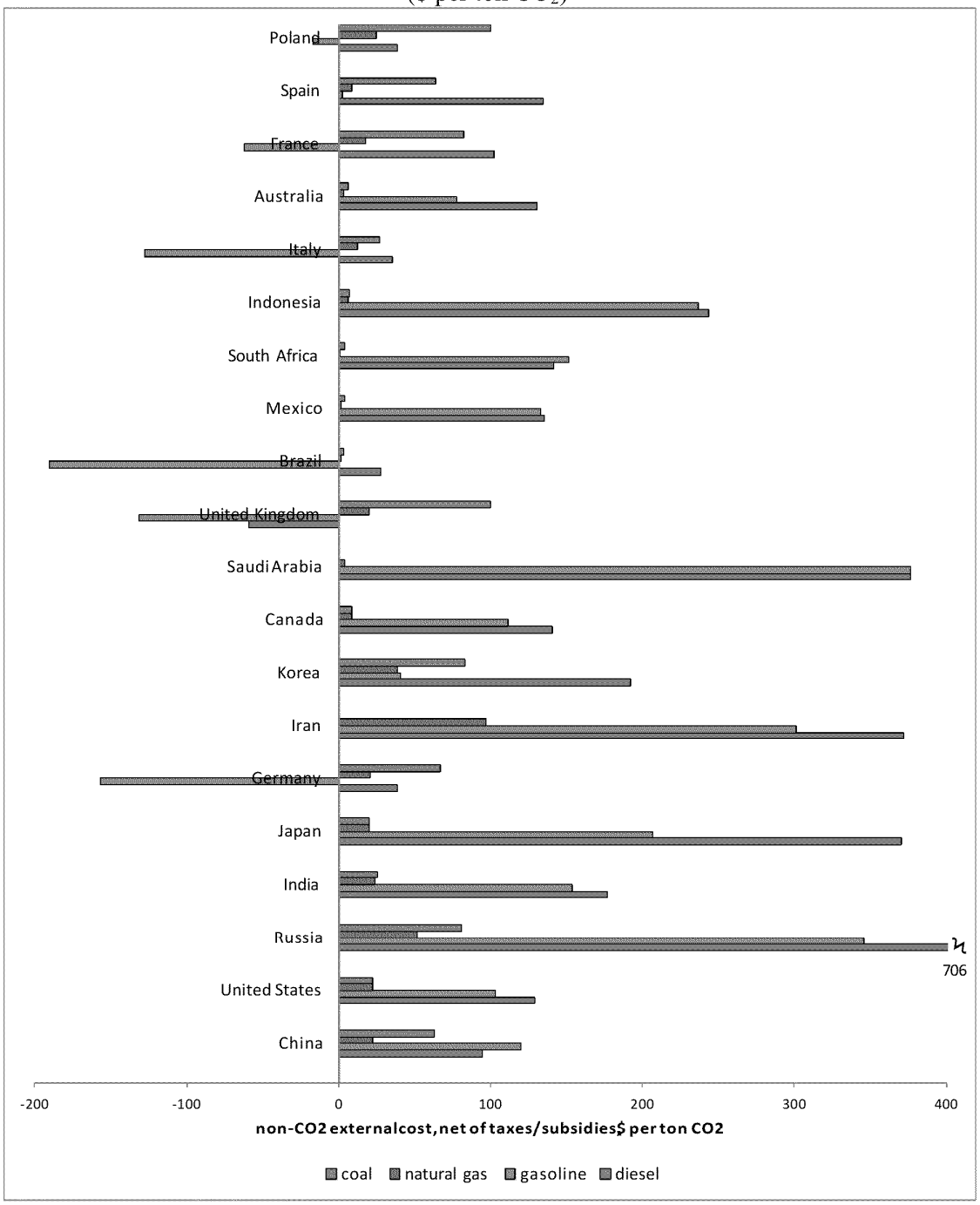
Fuel user prices ( ) for 2010 by country are taken from an IMF database (see Clements et al., 2013, pp. 143–44). These prices are compiled from various sources including publicly available data, survey data, reporting from country authorities, and extrapolations from international reference prices. Fuel excise tax (or subsidy) rates ( ) are from OECD (2010) and Clements et al. (2013)—where not available publicly, these reflect estimated price gaps between demand and supply prices.

Figure 5. Pre-Existing Fuel Taxes/Subsidies, 2010
($ per ton CO_2)



Source. Clements et al. (2013) and authors' calculations.
Note. Fuel taxes/subsidies per unit of fuels are divided by the fuel's emissions factor to express them in $ per ton of CO_2. Most countries do not significantly tax or subsidize coal or natural gas consumption.

Figure 6. Non-CO_2 External Costs by Fuel, Net of Taxes/Subsidies, 2010
($ per ton CO_2)



Source. Parry et al. (2014) and authors' calculations.
Note. Per unit external costs, net of fuel taxes/subsidies, are divided by the fuel's emissions factor to express them in $ per ton of CO_2.

Figure 5 shows pre-existing taxes/subsidies in 2010, expressed per ton of CO_2 (i.e., the tax/subsidy rate for a particular fuel divided by the carbon emissions factor for that fuel). There are no meaningful excises on coal and natural gas among the T20, and a handful of countries provide gas subsidies, for example, India (equivalent to \$19 per ton of CO_2), Iran (\$95) and Russia (\$18).[7] However, most countries levy sizeable motor fuel excises, equivalent to over \$100 per ton of CO_2 for gasoline in 12 countries and for diesel (which is frequently tax favored relative to gasoline) ten countries. However, motor fuels are heavily subsidized in Indonesia, Iran, and Saudi Arabia, where gasoline subsidies were between \$92 and \$193 per ton of CO_2 in 2010. An important caveat about the subsidies, however, is that to the extent they reflect differences in domestic and international fuel prices they vary from year to year with volatility in the latter. Moreover, the price-gap concept of a subsidy generally favored by economists is not accepted by all governments, especially if domestic prices recover domestic supply costs (the implications of ignoring subsidies are noted below).

(ii) Externalities

External costs ($\tilde{\tau}$) are taken from a recent IMF study (Parry et al. 2014). Given the uncertainties and controversies involved in quantification (e.g., how to value health risks in different countries) these estimates are best viewed as a starting point for discussion though they are based on conservative assumptions (e.g., in regard to air emission rates at coal plants—see below). Methodological details are summarized in the Appendix (given that this paper does not refine the methodology). Here we go straight to the numbers, which are for 2010.

Figure 6 shows the external cost estimates by fuel net of any taxes or subsidies—these estimates therefore reflect the gap between corrective taxes for non-CO_2 externalities and existing fiscal policies—again expressed per ton of CO_2 for that fuel. The external cost is simply the net external costs in Figure 6 plus the taxes (or less the subsidies) in Figure 5.

Non-CO_2 externalities for coal are positive in all cases (because air pollution costs are positive while existing taxes are essentially zero), exceeding \$50 per ton of CO_2 in eight cases, though they are moderate, for example, in South Africa, reflecting relatively low population exposure (given coastal proximities) and mortality risk values.[8] Net external costs

[7] Since 2010 Iran substantially scaled back gas and petroleum subsidies though some of the price increases were later lost to inflation and exchange rate depreciation (e.g., Salehi-Isfahani 2011, IMF 2014). The implications of subsidy reform are noted under Figure 7 below.

[8] Broadly speaking, the air pollution damages for coal are in the same ballpark as those in a study by West et al. (2013). Their approach is based on an air quality model that disaggregates the world into 14 regions. For 2030 (in year \$2005) they estimate global average health co-benefits of \$50-380 per ton of CO_2 reduced, with damages generally higher in developing than developed countries, and where the estimated range encompasses different scenarios for the valuation of health risks and pollution/health relationships. Nemet et al. (2010) review other studies, finding mean co-benefit estimates (in year 2008\$) of \$44 per ton of CO_2 in developed countries and \$81 for developing countries.

per ton of CO_2 for natural gas are typically much smaller than for coal.[9] For many countries, the next external cost from motor fuels is substantial, for example, over $100 per ton of CO_2 for diesel fuel for 14 countries (reflecting taxes undercharging of diesel fuel especially, due to unusually high air pollution damages, for Russia), though for five European countries and Brazil non-CO_2 costs for gasoline are negative (reflecting taxes in excess of corrective levels). The nationally efficient CO_2 price weights the net external costs from each fuel by their share in CO_2 reductions (see below) implying, for most countries, a disproportionately large weight applied to coal's external costs.

(iii) (Long-run) behavioral responses

Estimating country-level fuel price elasticities ( ) is well beyond the scope of this paper as it would require developing a consistent methodology (for example based on cross-sectional regressions, using a country-level data set) to develop these estimates. Instead, common elasticities across countries are assumed, taking a long-run perspective (after turnover of capital), based on the following discussion.

For the United States, a good starting point is the US Department of Energy's National Energy Modeling System (NEMS), which incorporates considerable detail on the energy sector and technology adoption, though the overall price responsiveness of fuel use in this model is viewed as conservative and tends to be somewhat smaller than implied by computable general equilibrium models. According to simulations from a variant of this model in Krupnick et al. (2010), the price elasticity for coal use in the United States (in response to a carbon tax, which takes into account the change in natural gas prices) is around -0.15. For comparison, the simple mean among eight studies of coal price elasticities (focusing on various OECD countries, China, and India) summarized in Trüby and Moritz (2011) is -0.28. A coal elasticity of -0.25 is used for the benchmark calculations here (for all countries)—coal is relatively price inelastic, given the large sunk investments and very long lives of coal plants.

Natural gas tends to be more responsive to changes in its own price, given its frequent role in supplying peak period (as opposed to baseload) power, though (in countries where coal and gas compete) this is dampened as carbon pricing drives up the price of coal relative to gas. Here the natural gas elasticity is also assumed to be -0.25.[10]

[9] There are some exceptions to this. For example, per unit of energy air pollution damages from coal plants with control technologies in the United States are about 85 percent larger than for natural gas plants. However, carbon emission rates at coal plants are about 70 larger, therefore air pollution damages expressed per ton of CO_2 are not very different for the two fuels (and gas receives a modest subsidy implying a still smaller difference in net external costs between the two fuels).

[10] For comparison, Liu (2004) estimates own price elasticities for natural gas (with no change in coal prices) of -0.24 to -0.36.

Numerous studies have estimated motor fuel (especially gasoline) price elasticities for different countries and the value assumed here, -0.5 for both gasoline and diesel, reflects, roughly speaking, a central value from the literature.[11]

C. Results

Benchmark estimates of nationally efficient carbon prices and their emissions impacts are first discussed, followed by a comparison of differentiated and uniform carbon pricing, and some sensitivity results.

(i) Nationally Efficient CO_2 Prices: Benchmark Estimates and Emissions Impacts

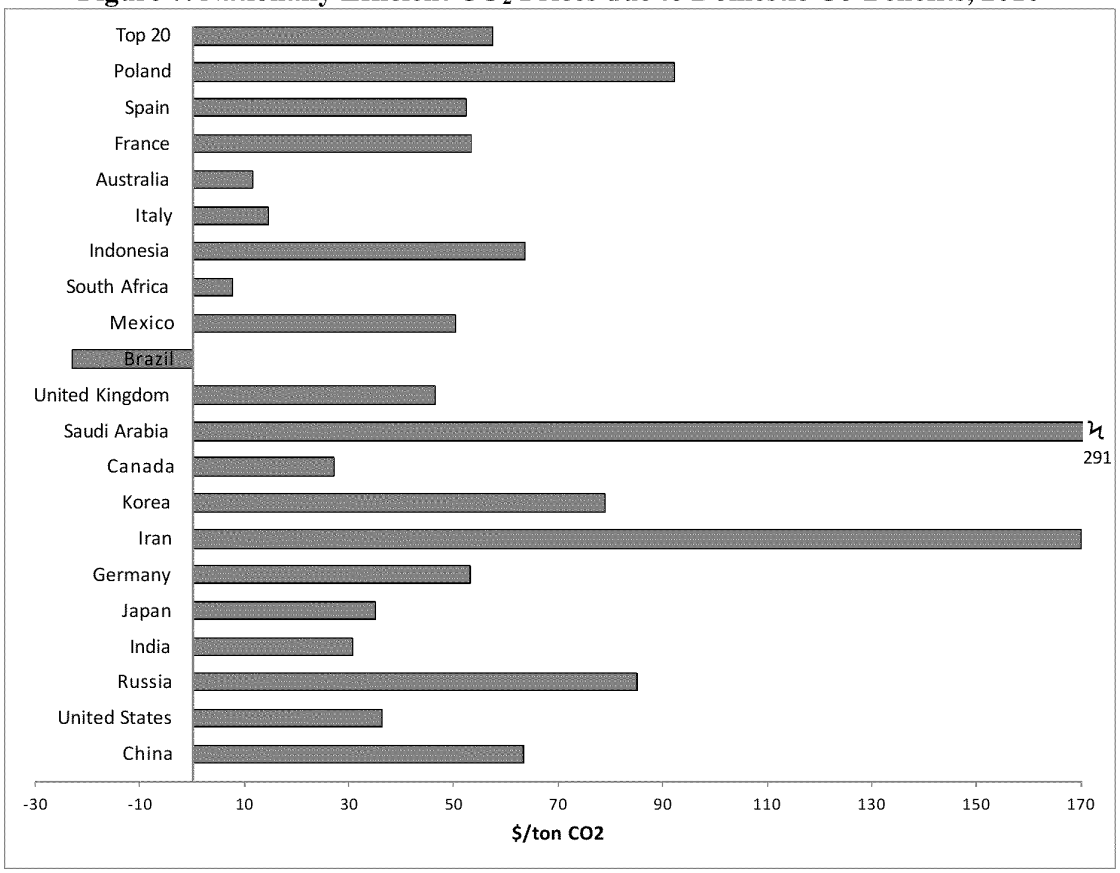
Figure 7 shows calculations of nationally efficient CO_2 prices for the T20 based on the above formulas and data. The average price for the T20 countries (with countries weighted by their emissions shares) is $57.5 per ton of CO_2 (all monetary figures are in US $ 2010).

Also striking is the cross-country variation in the nationally efficient CO_2 price—$291 per ton in Saudi Arabia (with terms of trade effects excluded), $63 per ton in China, $36 in the United States, $11.5 in Australia and -$23 in Brazil (i.e., Brazil on average overcorrects for co-benefits through pre-existing policies). The underlying determinants of these prices are discussed below.

Figure 8 shows the percent reduction in national, energy-related CO_2 emissions from imposing nationally efficient CO_2 prices, that is, the difference between estimated emissions that would have occurred with these prices in place in 2010, after full adjustment to these prices, and the actually observed emission levels in 2010. The figure also shows the contribution of individual fuels to those reductions.

[11] There is however significant variation among studies: for example, Sterner (2007) reports globally averaged (long-run) gasoline price elasticities of around -0.7 (or larger, in magnitude), while individual country estimates in Dahl (2012) are closer to about -0.25 on average.

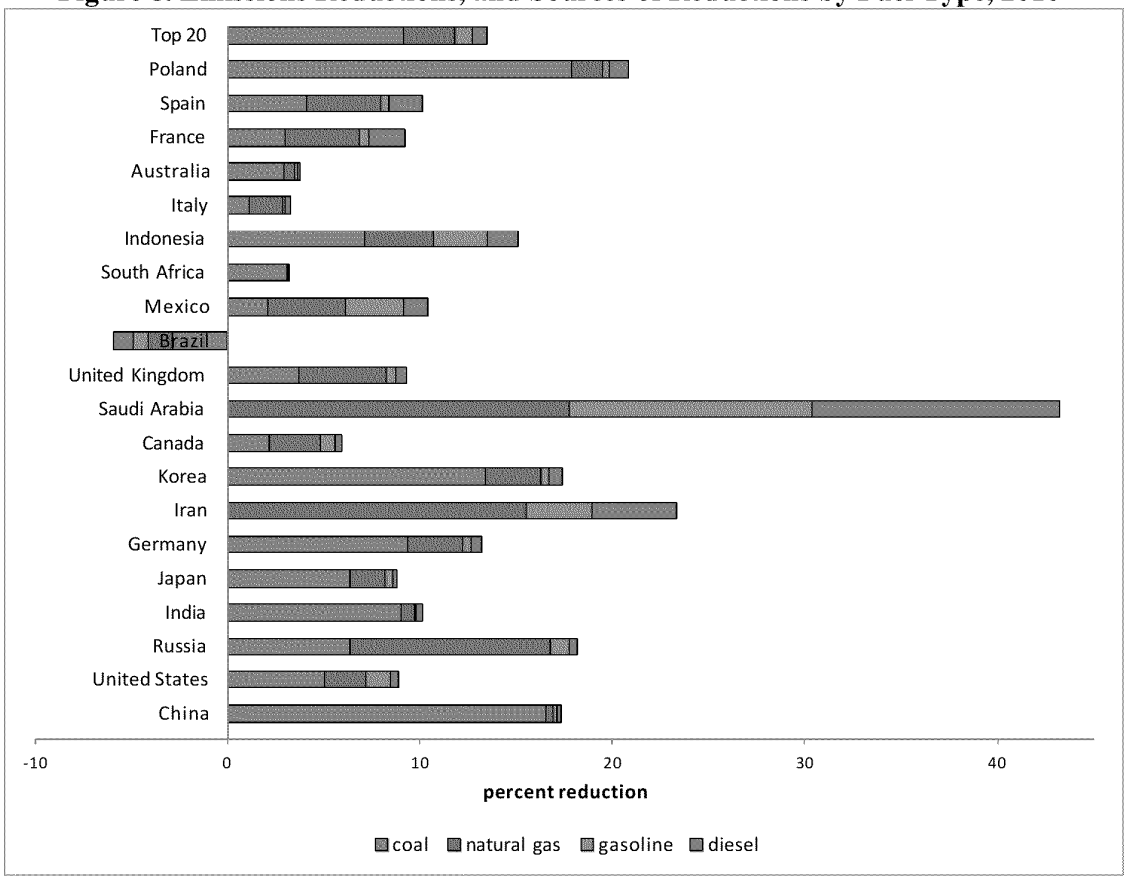
Figure 7. Nationally Efficient CO_2 Prices due to Domestic Co-Benefits, 2010



Source. Calculations using equation (3) and data discussed above.

Note. Figures show carbon prices that maximize domestic co-benefits (excluding climate benefits) net of climate mitigation costs (where costs do not account for broader fiscal linkages). Top 20 shows the price averaged across the top twenty emitters where individual country prices are weighted by their emissions shares. For Iran, calculations are based on fuel subsidies prevailing in 2010 which have since been reduced—if there had been so subsidies, the nationally efficient price for Iran would have been $52 per ton of CO_2.

Figure 8. Emissions Reductions, and Sources of Reductions by Fuel Type, 2010



Source. Calculations using equation (4) and data discussed above.
Note. Figure shows estimated emissions reductions in 2010 that would have occurred if nationally efficient CO_2 prices had been in place relative to actual emissions and the contribution of individual fuels to those reductions.

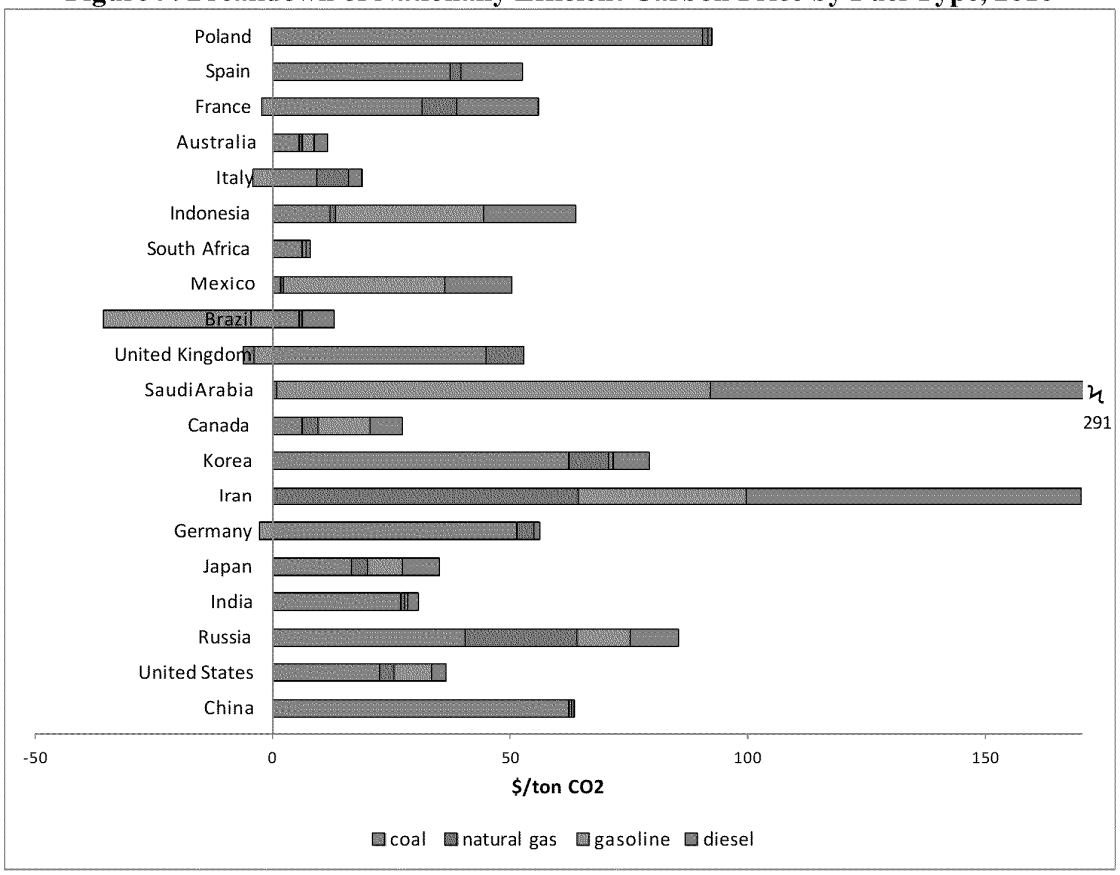
Total T20 emissions fall by 13.5 percent with nationally efficient CO_2 pricing. However, there is a good deal of variation across countries—emissions fall by over 40 percent in Saudi Arabia (the outlier) and over 15 percent in China, Iran, Indonesia, Korea, Poland, and Russia, while they fall by less than 6 percent in Australia, Canada, Italy, and South Africa (and increase in Brazil given the nationally efficient price is negative).

For most countries the bulk of the CO_2 reductions come from reduced coal use, because carbon pricing has a disproportionately large impact on coal prices (though this is dampened somewhat by the relatively low price responsiveness of coal compared with motor fuels) and coal has a high carbon emissions factor. For Saudi Arabia and Iran, the proportionate increase in motor fuel prices, and for gas in the case of Iran, is relatively large (given low, subsidized, prices for these fuels in 2010) and this leads to large CO_2 reductions from these fuels.

Figure 9 returns to the nationally efficient carbon price, showing the underlying contribution to it from individual fuels (i.e., breaking out the four terms aggregated in equation (3)). For 11 countries, coal accounts for the majority of the nationally efficient

carbon price. In Poland and China, for example, essentially all of the price reflects co-benefits from reduced coal use, because coal accounts for 86 and 95 percent of CO_2 reductions respectively, and co-benefits ton are very large, \$99 and \$64 per ton of CO_2 respectively (due to high air emissions rates and high population exposure to emissions).

Figure 9. Breakdown of Nationally Efficient Carbon Price by Fuel Type, 2010



Source. Calculations using equation (3) and data discussed above.

In Italy and Brazil, co-benefits are more moderate as there is little use of coal, and motor fuel taxes in these countries are close to or exceed estimates of corrective taxes. Iran and Saudi Arabia do not use coal, and so all of the CO_2 reduction comes from reduced use of motor fuels, and gas in Iran's case—for motor fuels in particular, there is a large gap between current taxes (which are negative for these countries) and corrective taxes, implying large co-benefits per ton of CO_2 reduced. As already noted, not all countries agree with the price-gap measure of subsidies, but even if subsidies are excluded from the calculations, the nationally efficient CO_2 price in Saudi Arabia, for example, is still large at over \$130 per ton of CO_2.[12]

[12] Corrective motor fuel taxes for Saudi Arabia are in the same ballpark as those, for example, for China (road congestion is less severe in Saudi Arabia, though Saudi Arabia has higher traffic accident externalities, and due to higher income, an hour of travel delay is valued more). A sizable portion of the CO_2 reductions in Saudi

(continued…)

(ii) Net Benefits with Differentiated and Uniform Carbon Pricing

Figure 10 shows the net economic benefits (excluding climate benefits and not accounting for broader fiscal interactions) from carbon pricing for the T20 countries (from equation (2)), expressed as a percent of GDP. Net benefits are shown under both nationally efficient CO_2 pricing and when T20 countries all price emissions at the same rate ($52 per ton) to achieve the same emissions reduction (13.5 percent) in total for T20 countries as under nationally efficient pricing.

Under differentiated prices, net benefits average 0.20 percent of GDP across T20 countries. However, the gains are larger in China (0.70 percent of GDP) and Russia (0.76 percent of GDP), and much higher still in Saudi Arabia (3.09 percent).

Under the uniform pricing regime, net benefits for the T20 countries average 0.16 percent of GDP—thus there is a sizeable, though not dramatic, extra benefit (23 percent) from differentiated pricing over uniform pricing, in part because the nationally efficient prices in some of the big emitting countries are not that different from the uniform price. But there are some cases where uniform pricing substantially reduces net benefits for individual countries. For example, in Australia, Brazil, Italy, and South Africa the uniform price causes a net domestic cost, instead of a gain under (much lower) nationally efficient prices. Net benefits from Saudi Arabia are also reduced considerably for the opposite reason (the uniform price being far below the nationally efficient price).

(iii) Sensitivity Analyses

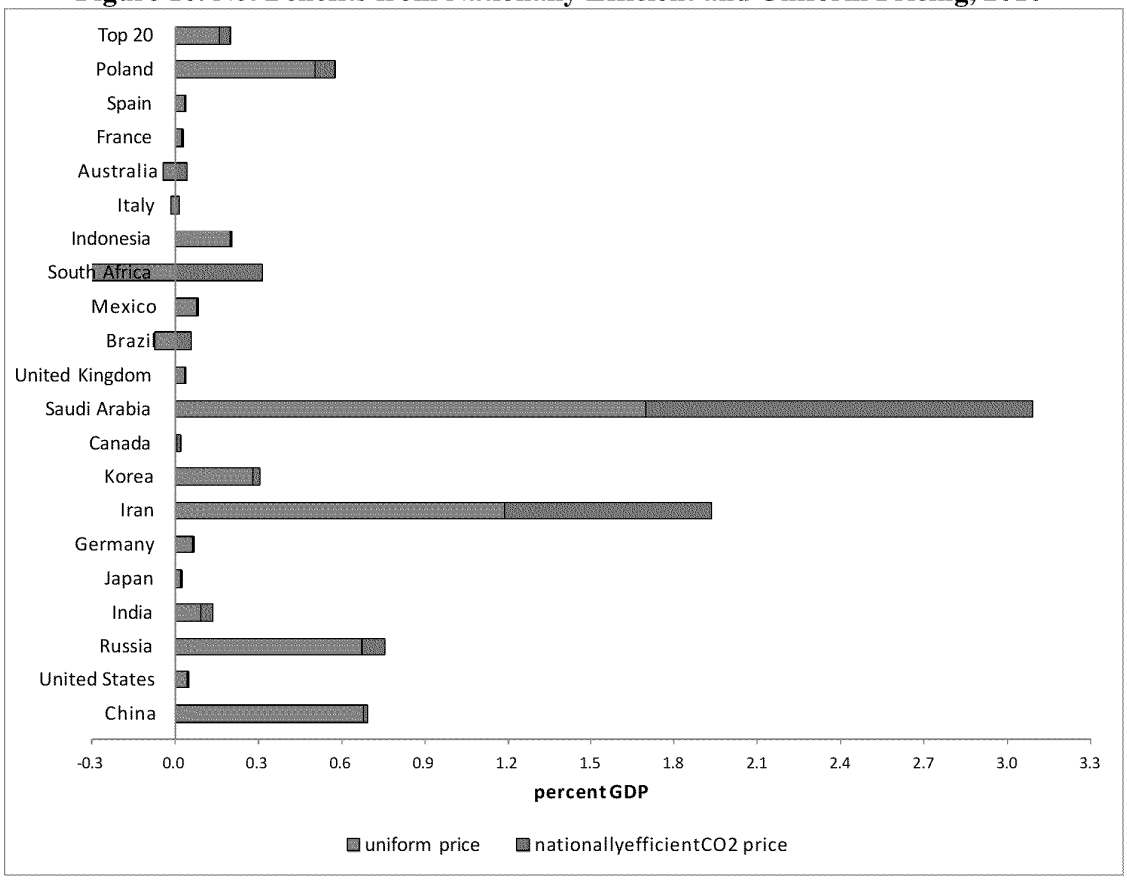
Table 1 reports results for the T20 countries as a whole, and China (the biggest emitter), for three sets of sensitivity analyses.

The first uses air pollution damages estimates for coal from Parry et al. (2014) that are based on current emissions rates averaged across all existing coal plants, including those with and those without air emissions control technologies. The above co-benefit estimates are based on the average emissions rates across only plants with control technologies. Which assumption is more appropriate is not entirely clear, given that current average emission rates are likely to be on a downward trend with greater future deployment of control technologies.

The higher emissions rate implies larger co-benefits from carbon pricing. In fact the nationally efficient CO_2 price for the T20 as a group increases by about 50 percent to $85.5 (and the associated emissions reductions rise to 17.6 percent), while the nationally efficient price for China, where deployment of emissions control technologies is less common than among the T20 as a whole, increases by 93 percent to $122.1 per ton.

Arabia come from reduced use of natural gas (Figure 8) but, given the small co-benefits from reducing gas, this contributes minimally to the nationally efficient price in Figure 9.

Figure 10. Net Benefits from Nationally Efficient and Uniform Pricing, 2010



Source. Calculations using equation (2) and data discussed above.
Note. Net benefits are domestic environmental benefits less CO_2 mitigation costs reflecting behavioral responses, such as power generators using cleaner but more expensive fuels and motorists driving less than they would otherwise prefer.

Adjusting all fuel tax elasticities by the same proportion has no effect on the nationally efficient CO_2 price (see above), though the emissions reductions from these prices obviously vary. For the T20 group of countries, CO_2 emissions reductions vary between 7.1 and 19.3 percent as all fuel price elasticites are reduced and increased by 50 percent. Raising the price elasticities for coal and natural gas up to those for motor fuels (while holding those for motor fuels fixed) also increases the emissions reductions considerably. The nationally efficient prices for the T20 fall modestly in this simulation however (to $52.3 per ton)—on average, the co-benefits per ton of CO_2 associated with reducing coal and natural gas are less than the co-benefits per ton from reduced use of motor fuels.

Table 1. Sensivity Analysis

	nationally efficient carbon price $/ton CO_2	percent reduction in CO_2	net benefits percent of GDP
Baseline case			
Top 20 Emitters	57.5	13.5	0.20
China	63.4	17.3	0.70
Coal air pollution damages based on average emissions across all plants (rather than only those with controls)			
Top 20 Emitters	85.5	17.6	0.39
China	122.1	25.2	1.95
Behavioral responses to carbon pricing			
all fuel elasticities increased 50 percent			
Top 20 Emitters	57.5	19.3	0.28
China	63.4	24.8	1.00
all fuel elasticities reduced 50 percent	57.5	7.1	0.11
Top 20 Emitters	63.4	9.1	0.36
China			
coal and natural gas elasticities increased to those for motor fuels			
Top 20 Emitters	52.3	22.3	0.30
China	63.0	31.1	1.24
Non-carbon external costs			
increased 50 percent			
Top 20 Emitters	85.7	17.6	0.36
China	95.7	22.1	1.34
halved			
Top 20 Emitters	29.3	7.7	0.08
China	31.1	10.6	0.21

Finally the results are obviously sensitive to different assumed values for non-CO_2 external costs. The nationally efficient CO_2 prices for the T20 countries as a whole vary between $29.3 and $85.7 per ton as these damage values are reduced and increased by 50 percent. If anything the non-CO_2 damage values used in the baseline estimates are likely on the low side (e.g., due to conservative assumptions about coal emission rates).

D. Fiscal Considerations

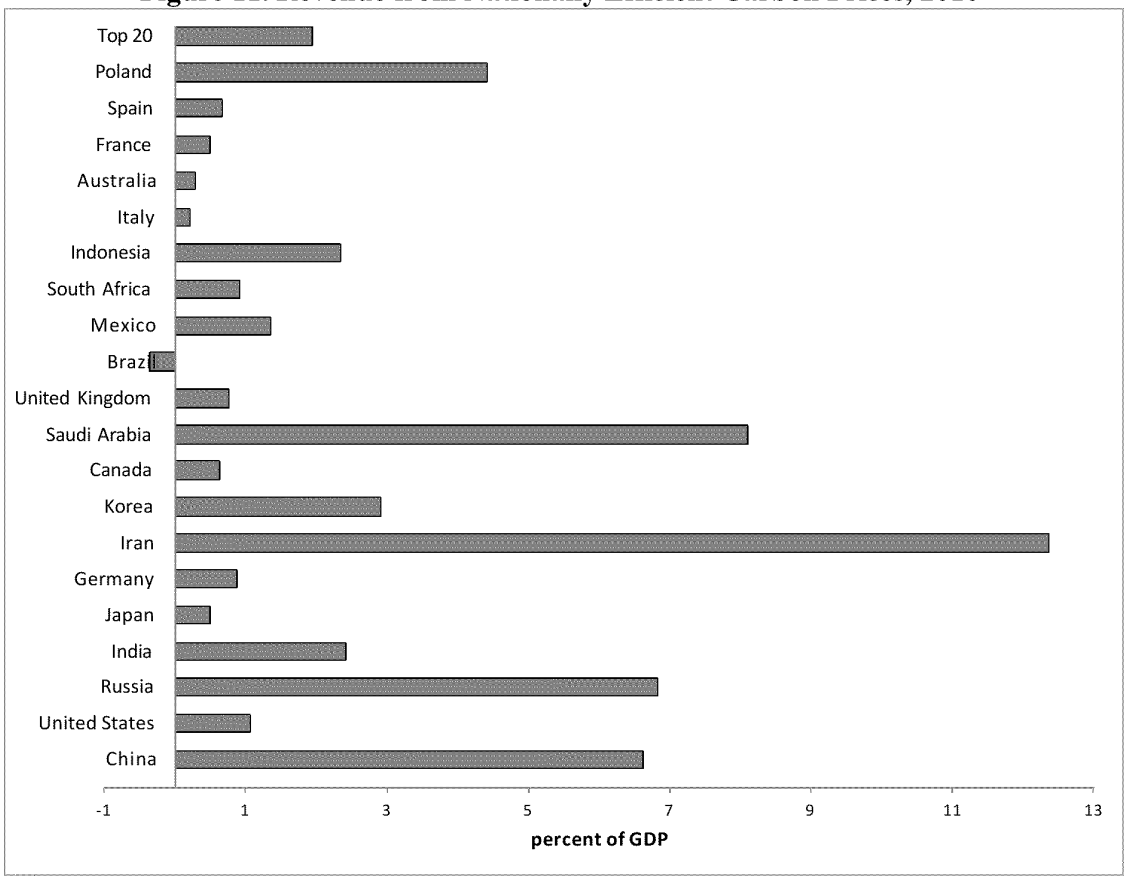
After noting how much revenue is raised from carbon pricing, this section discusses how fiscal linkages influence the net economic benefits of carbon pricing policies.

As indicated in Figure 11, nationally efficient carbon pricing policies can raise substantial amounts of revenue—above 6 percent in China, Russia, Iran, and Saudi Arabia. The average for the T20 countries is 1.9 percent of GDP, which is still very substantial, though reflects the large influence of the United States (where carbon pricing revenues are 1.1 percent of GDP), given that country-level revenues are weighted here by country shares in T20 GDP.

Broader taxes in the fiscal system (taxes on personal and corporate income, payrolls, and consumption) burden the economy by creating two sorts of distortion to economic activity. First, the tax system distorts factor markets, thereby reducing the overall *level* of economic activity. By lowering the net of tax return from working, and therefore discouraging labor force participation, effort on the job, and so on, taxes on labor income reduce work effort below levels that would otherwise maximize economic efficiency. Similarly, by lowering the net of tax returns on investments in (physical and human) capital, these taxes reduce capital accumulation below economically efficient levels. Second, taxes also distort the *composition* of economic activity, most obviously by encouraging more activity in the informal sector (where productivity tends to be lower than in the formal sector), and also causing a bias towards other tax-sheltered activities or goods (e.g., tax preferences for owner occupied housing cause people to spend more on housing and less on ordinary goods than they would otherwise prefer, lowering the value of their purchasing power). Over the last two decades, public finance economists have emphasized the critical importance of considering the full range of behavioral responses—the composition as well as the level effect—when evaluating the economic costs of the tax system (e.g., Gruber and Saez 2002, Feldstein 1995, 1999, Saez et al. 2010).

Carbon taxes (or tax-like instruments) interact with the broader fiscal system in two important ways. First, large efficiency gains are generated when revenues are used to lower other distortionary taxes (or for other purposes producing comparable gains in economic efficiency)—this is termed the 'revenue-recycling' effect. Second, however, higher energy prices tend to compound the distortions from taxes in factor markets by reducing (via a contraction in overall economic activity) work effort and capital accumulation.

Figure 11. Revenue from Nationally Efficient Carbon Prices, 2010



Source. Calculations using above equations and data.

Note. The average for the top 20 emitters weights countries revenue to GDP ratio by their shares in total GDP (which raises the influence of countries with high GDP like the United States). Revenue here is measured simply by the CO_2 emissions price times CO_2 emissions, accounting the price-induced reduction in emissions, but ignoring interactions with other tax bases (e.g., for pre-existing fuel taxes).

Up to a point (i.e., so long as the reduction in the base of the carbon tax is not too great), there can be a net economic gain from these two effects (the revenue-recycling effect dominates the tax-interaction effect). Basically, this is because cutting broader taxes helps to reduce distortions both to the level, and the composition, of economic activity, while although higher energy prices can lower the level of economic activity they do not, to an approximation, worsen distortions in the composition of economic activity.[13]

However, the more important point is that if revenue opportunities are not exploited, for example allowances are freely allocated in a trading system or carbon tax revenues are earmarked for spending projects that do not significantly increase economic efficiency, then fiscal linkages considerably increase the costs of carbon pricing policies—perhaps by enough to more than offset the gains from pricing environmental damages! This follows because such polices fail to counteract the adverse tax-interaction effect with revenue-recycling benefits.

Formulas from the literature[14] are applied here to adjust the net benefits from nationally efficient carbon pricing from the previous section to account for the two linkages with the broader fiscal system, comparing cases with recycling benefits (revenues are used to cut other distortionary taxes) and with no recycling benefit (revenues are returned in lump-sum transfers). The calculations are inescapably very crude, given the scarcity of empirical work on the economic costs of the broader tax system, at least beyond the United States. The calculations assume that—for each country—using revenue to reduce other taxes results in an efficiency benefit of $0.25 per $1 of revenue recycled and that 60 percent of this gain comes from increases in the level of economic activity and 40 percent from reduced distortions to the composition of economic activity.[15]

Figure 12 summarizes the results. The orange bars simply reproduce the net benefits from nationally efficient (i.e., differentiated) carbon pricing from Figure 8.

The green bars in Figure 12 indicate the additional gain from fiscal linkages when revenues are used to cut other taxes (i.e., the revenue recycling benefit less the cost of the tax-interaction effect). For the T20 countries as a whole, net benefits double to 0.33 percent

[13] This follows if the energy intensity of tax-favored sectors (like housing) is not too different from that for the economy as a whole (Parry and Bento 2000), or if the informal sector largely supplies low-energy-intensive goods and services (Bento et al. 2012). Some early papers (e.g., Bovenberg and Goulder 1996, Parry 1995) suggested that the revenue-recycling benefit falls short of the tax-interaction effect, implying that fiscal interactions lower the net benefits of carbon tax swaps. However, these studies substantially understate revenue recycling benefits as they do not capture distortions to the composition of economic activity caused by the broader tax system (see Parry and Bento 2000).

[14] See Parry and Williams (2010), pages 9-10 (after simplifying to one household group). Similar formulas have been shown to yield results that are approximately consistent with detailed numerical models (e.g., Goulder et al. 1999).

[15] The total private sector benefit (the $1 transfer plus the gain in economic efficiency) is $1.25. These figures are based on an assessment of US evidence in Parry and Williams (2010).

of GDP—for some countries the proportionate increase in net benefits is much greater still (e.g., more than 200 percent in eight countries). The bottom line from these, albeit very course, calculations is that fiscal considerations appear to significantly reinforce the net benefits from carbon pricing if revenues are used to substitute for other distortionary taxes.

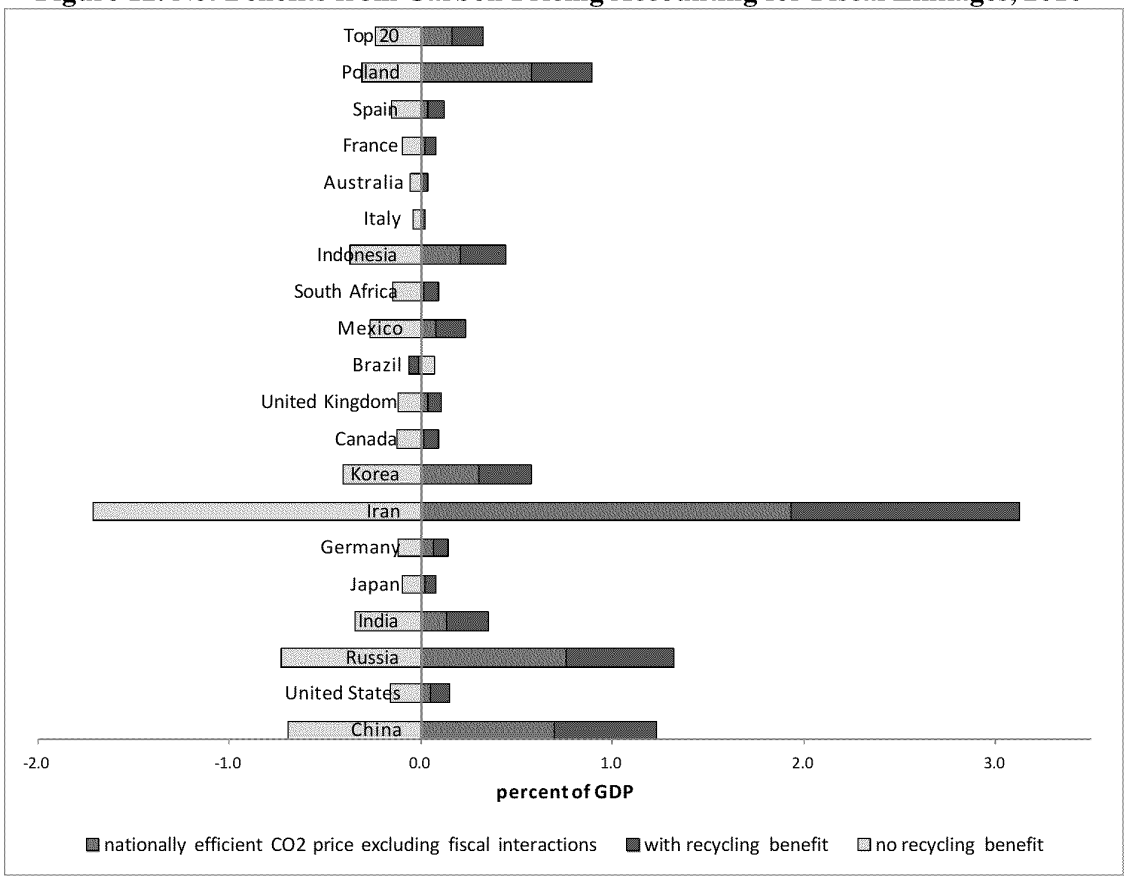
On the other hand, the grey bars in Figure 12 suggest that carbon pricing produces net economic costs—not net benefits—when there are no recycling benefits. That is, the economic costs from the tax-interaction by itself (when it is not counteracted by the revenue recycling benefit) outweigh the gains from pricing co-benefits. This underscores the importance, long emphasized in the literature (e.g., Parry et al. 1999) of implementing carbon pricing as part of a tax shift, rather than an increase in the tax burden—unless the extra government spending yields gains in economic efficiency that are comparable to those from reducing distortionary taxes.

III. Conclusion

This paper provides calculations of nationally efficient CO_2 prices, that is, prices to reflect domestic externality benefits (net of any internalization through fuel taxes/compounding through subsidies and excluding climate-related benefits) for reducing use of coal, natural gas, and motor fuels, for the top twenty CO_2-emitting countries.

On average these prices are quite high, $57.5 per ton of CO_2, suggesting that (most) high-emitting countries need not wait on global coordination to move ahead with carbon pricing programs because the domestic environmental benefits (dominated, in many cases, by reductions in pollution-related deaths) exceed the mitigation costs. Nationally efficient CO_2 prices vary substantially across countries however (with population exposure to coal's air emissions, road congestion, health risk valuation, pre-existing fuel taxes/subsidies, etc.), raising a question mark over the desirability of price harmonization measures (like linking of trading systems). Moreover, a key finding from prior literature on carbon pricing remains robust—if carbon pricing revenues are overly used for low-value purposes (or revenues are forgone by free allocation in trading systems) the overall welfare impacts can be negative rather than positive. Ideally, carbon pricing is part of a broader tax shifting operation that lowers other taxes in the fiscal system with the new revenues from carbon taxes (or allowance auctions).

Figure 12. Net Benefits from Carbon Pricing Accounting for Fiscal Linkages, 2010



Source. Net benefits from Figure 10 for the nationally efficient price are adjusted for fiscal linkages based on formulas in Parry and Williams (2010) and assuming an efficiency benefit of $0.25 per $1 of revenue used to reduce distortionary taxes with 60 percent of this benefit due to increases in the level of economic activity and 40 percent from reduced distortions to the composition of economic activity.

Note. The orange bars, replicated from Figure 8, show the net benefits from nationally efficient pricing when linkages with the broader fiscal system are (incorrectly) ignored. The green bars indicate net efficiency benefits from fiscal interactions when revenue is used to cut other distortionary taxes. The grey bars show net efficiency costs from fiscal interactions in the absence of recycling benefits.

Appendix: Methodology Underlying non-CO_2 External Damages

This Appendix discusses the valuation of air pollution damages from stationary sources, and externalities from motor vehicles, that underlie the co-benefit estimates used above.

Air Pollution from Coal and Natural Gas. The key air pollutant from a public health perspective is fine particulate matter ($PM_{2.5}$, with diameter up to 2.5 micrometers), which is small enough to penetrate the lungs and bloodstream. $PM_{2.5}$ can be emitted directly during fuel combustion, or formed indirectly through chemical reactions in the atmosphere involving sulfur dioxide (SO_2) and nitrogen oxide (NO_x) emissions.[16]

Parry et al. (2014) assess damages from these pollutants for coal plants by first estimating 'intake fractions'—the fraction of these emissions that are inhaled by exposed populations as $PM_{2.5}$. They begin with state-of-the-art estimates (Zhou et al. 2006) of these fractions for the average coal plant in China, where these estimates account—given that pollution from tall smokestacks can be transported great distances—for exposure to people living up to 2,000 km from plants. Parry et al. (2014), extrapolate intake fractions to other countries depending on the number of people living at different distance classifications from the average coal plant in that country relative to the number of people living in those distance classifications in China. This is done by mapping data on the location of coal plants (in over 100 countries) to very granular, spatial population data.[17] Note that some of the air pollution deaths will be across the border (given the long-range transport of pollution from tall smokestacks) so not all of the co-benefits from carbon pricing are strictly national benefits.

Intake fractions are then linked to mortality risks. Baseline mortality rates are estimated for diseases (e.g., lung cancer, heart disease) whose prevalence is potentially increased by pollution exposure, using data on age structures for each country and regional average mortality rates by age/type of disease estimated in the Global Burden of Disease (GBD) project.[18] These baseline mortality rates are then scaled by intake fractions and evidence (again from GBD) on how the relative risk for each disease increases with the rate at which pollution is inhaled, to give health impacts per ton of emissions for the three air pollutants.

---

[16] The possible global cooling benefits of particles, which can reflect sunlight, are not considered here.

[17] The main limitation of this approach is that it assumes emissions in another country have the same impact on ambient pollution concentrations at different differences from a coal plant as in China. This will not be the case, for example, if wind speeds and directions are very different in the other country compared with average conditions in China. However, studies suggest population exposure is usually a far more important determinant of health damages than differences in meteorology (e.g., Zhou et al. 2006). Moreover, Parry et al. (2014) report some cross-country checks from a regional air quality model (that does take meteorology into account) suggesting the extrapolations may not be too far off in most cases and that there is no systematic pattern to the direction of bias.

[18] See Burnett et al. (2013). Baseline mortality rates vary substantially across countries—for example, rates are relatively low in Sub-Saharan Africa where people are less likely to survive long enough to die from diseases that can be exacerbated by pollution.

Health risks are then monetized. There is solid empirical evidence suggesting that people's willingness to pay to reduce health risk[19] rises with real income—according to a meta analysis of several hundred stated preference studies by OECD (2012), each one-percent increase in real income increases mortality values by 0.8 percent. Using this statistic, relative per capita income, and a starting value for the average OECD country ($3.7 million per premature death, updated from OECD 2012), Parry et al. (2014) infer mortality values for all countries, and hence damages per ton of emissions.

Finally, environmental damages can be expressed per gigajoule (GJ) of coal energy using country-level estimates of emissions rates per GJ[20]—that is, the damage per GJ is the emission rate, times the damage per ton of emissions, summed over the three pollutants. The damage estimates underlying the main results below are conservatively based on average emission rates at coal plants currently employing control technologies. Using national average emission rates produces higher damages estimates (as reported in sensitivity analysis) to the extent that existing plants lack controls (or have them but fail to operate them), though these average rates will typically decline in future as newer (usually cleaner) plants progressively replace older plants.[21]

Parry et al. (2014) used the same approach as above to estimate air pollution damages per GJ of natural gas from power plants, though these damages are far more moderate as gas produces minimal amounts of direct $PM_{2.5}$ and SO_2, and is also less NO_x intensive than coal.[22] Air pollution damages for gas used in residences and industry were estimated in the same way as for motor fuels (see below) but, since the estimates are similar to those for gas power plants, the latter are used here for all natural gas usage.

Vehicle Externalities. Co-benefits from incorporating carbon charges in motor fuels include reduced air pollution, traffic congestion, accidents and (for the case of heavy trucks) road damage.

Air emissions from motor fuel combustion are released close to the ground and tend to remain locally concentrated rather than being dispersed over large distances. For these fuels, Parry et al. (2014) extrapolate national average intake fractions for emissions in

[19] Or more precisely, the 'value of a statistical life', that is, people's willingness to pay for reductions in mortality risk, expressed per life saved.

[20] There is less variation in local air emissions rates when expressed per unit of energy as opposed to per ton of coal.

[21] We gratefully acknowledge the help of Fabian Wagner who provided local air and carbon emissions factors for coal and other fuels which were calculated from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, developed by the International Institute for Applied Systems Analysis (IIASA).

[22] These estimates are for conventional gas (environmental costs might be somewhat higher for shale gas produced, for example, in the United States and Russia).

different countries (based on average results from a large city-level database). Mortality effects and monetary damages are then inferred using the same procedures as above, and damages are expressed per liter of fuel use, based on country-level vehicle emission rates. For most countries, air pollution damages from gasoline are small relative to congestion and accident externalities, but are more substantial for diesel due to higher emission rates.

For the congestion component of corrective motor fuel taxes, what is needed is the value of extra travel (i.e., marginal) delay to other road users, averaged across urban and rural roads and peak and off-peak periods, due to an extra car kilometer driven. Parry et al. (2014) obtain rough estimates of this as follows.

First, average travel delay—the difference between time taken to drive a km at prevailing speeds and the time that would be taken at free-flow speeds—was estimated. Due to lack of better data, national average travel delays were extrapolated from a database containing 90 cities in different countries. Statistical regressions were used to relate travel delays to various transportation indicators at the city level, and then country level delays were predicted using the regression coefficients and country-level data for the same transportation indicators.

Second, marginal delay is inferred from average travel delay. It turns out that under a commonly-used specification for the relationship between travel speeds and traffic volume, marginal delay is a simple multiple of average delay—Parry et al. (2014) use a multiple of 4 (which, from the transportation engineering literature, seems a reasonable rule-of-thumb for congestion in urban centers).

Third, marginal delays are converted into passenger delays by scaling by car occupancy and are then expressed in monetary costs using the value of travel time which, based on reviews of empirical literature, is taken to be 60 percent of the market wage. Finally, marginal congestion costs are scaled back by a third, based on evidence suggesting that travel on congested roads (which is dominated by commuting) is less responsive to higher fuel prices than travel on uncongested roads.[23]

Parry et al. (2014) assess accident externalities by first breaking out country-level data on traffic fatalities into those assumed to reflect external risks, including pedestrian/cyclist fatalities and a fraction of fatalities in multi-vehicle collisions (as opposed to internal risks from single-vehicle collisions) and monetizing them using the same mortality values as used for pollution deaths. Other external costs (e.g., non-fatal injuries to pedestrians/cyclists, medical/property damages borne by third parties) are extrapolated from a limited number of country case studies.

[23] The congestion cost estimates are understated as they ignore some broader costs. For example, people may set off earlier or later to avoid the rush-hour peak, causing them to arrive earlier or later at their destination than they would otherwise prefer. Congestion also results in day-to-day uncertainty over travel times, making it more difficult to plan the day. Congestion costs can also be substantially higher when buses—which have high vehicle occupancies—account for a sizable share of vehicle kilometers.

Lastly, Parry et al. (2014) measure the external costs of road damage by countries' spending on road maintenance, scaled back by 50 percent to crudely adjust for the role of weather in road deterioration.

Combined external costs from motor fuel use are summarized by the corrective (or Pigouvian) taxes. For gasoline, corrective taxes are based on externalities from cars, and for diesel, on a weighted average of externalities from (diesel) cars and trucks with weights equal to the respective fuel shares of these vehicles.[24] In computing corrective taxes, externalities are scaled back to take into account the fact that only a fraction of the tax-induced reduction in fuel use comes from reductions in vehicle kilometers driven (the other fraction comes longer-run improvements in vehicle fuel economy which has no impacts on congestion, accidents, and road damage).

[24]Congestion costs per vehicle kilometer for trucks are taken to be twice those for cars.

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To: McGartland, Al[McGartland.Al@epa.gov]
Cc: Durham, Natalie[Durham.Natalie@epa.gov]; Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: Roberts, Martha
Sent: Wed 7/22/2015 4:28:18 PM
Subject: RE: quick check in on SCC congressional

Sure, that sounds great. I'm happy to walk over and I'll come at 2.

I will try to get more from OAR on what draft language they already have. It sounds like they think they may already have what we need for the response letter, so hold off on working on that for now. No need to reinvent the wheel.

From: McGartland, Al
Sent: Wednesday, July 22, 2015 12:19 PM
To: Roberts, Martha
Cc: Durham, Natalie; Kopits, Elizabeth
Subject: quick check in on SCC congressional

Hi. The SCC team is meeting on july 23 (Thursday) from 2:00 to 2:45. Would you be able to call into it for 10 minutes to talk about the SCC letter? We can be flexible on the timing within that window of 2:00 – 2:45.

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]; Beauvais, Joel[Beauvais.Joel@epa.gov]
Cc: Rennert, Kevin[Rennert.Kevin@epa.gov]; McGartland, Al[McGartland.Al@epa.gov]; Marten, Alex[Marten.Alex@epa.gov]
From: Roberts, Martha
Sent: Wed 7/22/2015 2:44:55 PM
Subject: RE: 7.21.2015_JMI et al to EPA re SCC docs.pdf

I got looped into emails on this between OCIR and OAR and have a few questions for you all.

First, on the scope of the documents requested. I mentioned the prior SCC FOIA releases that you all worked on, and that there may be some/a lot of overlap between this inquiry and those FOIAs. Could you send me the original SCC FOIA requests as well as any further clarification that was made of those requests. In particular, what custodians were identified in the FOIA requests, and what search terms were used? Also, did you use Lotus Notes to collect and organize the documents for the FOIAs, or another database (e.g. Relativity)?

Second, on the response letter. While we are collecting potentially responsive documents, OCIR is hoping that we in OP can start putting together a draft response letter for OAR to review. OAR has said that they have language from other letters that we likely could/should use. Do we have language from other contexts that we could pull? Do you all have enough to get started on a draft? If it would be helpful to have a meeting first, it sounds like it would be a good idea to move up the already scheduled SCC meeting on Tuesday.

Thanks,

Martha

-----Original Message-----
From: Kopits, Elizabeth
Sent: Tuesday, July 21, 2015 5:46 PM
To: Beauvais, Joel
Cc: Rennert, Kevin; McGartland, Al; Marten, Alex; Roberts, Martha
Subject: Re: 7.21.2015_JMI et al to EPA re SCC docs.pdf

Thanks Joel. Our next SCC meeting with you is currently scheduled for next Tuesday (7/28) am. But please let me know if you would like to talk before then too.

Elizabeth

Sent from my iPhone

> On Jul 21, 2015, at 5:30 PM, "Beauvais, Joel" <Beauvais.Joel@epa.gov> wrote:
>
> FYI - we can discuss further when appropriate
>
> <7.21.2015_JMI et al to EPA re SCC docs.pdf>
>
>
>
>

To: Kopits, Elizabeth[Kopits.Elizabeth@epa.gov]
From: Kopits, Elizabeth
Sent: Tue 9/1/2015 10:22:04 AM
Subject: Fw:
Elke_TP.docx

From: Kopits, Elizabeth
Sent: Tuesday, September 1, 2015 6:14 AM
To: Kopia, Katherine
Subject:

To: McGartland, Al[McGartland.Al@epa.gov]; Bowen, Jennifer[Bowen.Jennifer@epa.gov]
Cc: Snyder, Brett[Snyder.Brett@epa.gov]
From: Kopits, Elizabeth
Sent: Wed 8/26/2015 4:41:10 PM
Subject: RE: SCC entry for weekly update

P.S. NAS media advisory should go out this afternoon, so the wording I drafted below is accurate.

From: Kopits, Elizabeth
Sent: Wednesday, August 26, 2015 11:26 AM
To: McGartland, Al; Bowen, Jennifer
Cc: Snyder, Brett
Subject: SCC entry for weekly update

Sure, no problem. Here is an entry for SCC. I am pretty sure that by Friday the media advisory can be noted in past tense but I am double checking on this now. Will let you know once I hear back from NAS. Also, if you think the second parenthetical below is unnecessary then feel free to delete.

Social Cost of Carbon: The National Academies' has posted general information about the SCC project on their website, including committee membership, and has issued a brief media advisory about the first committee meeting. On September 2nd, at the portion of the meeting that is open to the public, representatives from of the interagency working group (CEA and EPA-NCEE) will give two background presentations (reviewing the charge and SCC methodology) and be available to answer technical questions from the committee members.

Thanks,

Elizabeth

From: McGartland, Al
Sent: Wednesday, August 26, 2015 5:57 AM

To: Bowen, Jennifer
Cc: Snyder, Brett; Kopits, Elizabeth
Subject: Re: entry from Chris M for weekly update

This is fine. Elizabeth can you do a blurb on the NAS SCC again. If can be short and reference earlier entries.

Sent from my iPhone

On Aug 25, 2015, at 5:05 PM, Bowen, Jennifer <Bowen.Jennifer@epa.gov> wrote:

HI Al,

Non-Responsive

Jenny

From: Moore, Chris
Sent: Tuesday, August 25, 2015 1:35 PM
To: Bowen, Jennifer
Cc: McGartland, Al
Subject:

Hi Jenny,

Al suggested that I write a few sentences for the weekly update describing the recent

Non-Responsive

Chris

Non-Responsive

To: Wolverton, Ann[Wolverton.Ann@epa.gov]
Cc: Marten, Alex[Marten.Alex@epa.gov]
From: Kopits, Elizabeth
Sent: Wed 8/26/2015 2:02:59 PM
Subject: RE: Climate team: Please send me agenda items by noon today. Thanks! (NT)

Ann – I'm not going to be at climate team today. Sorry. Ex 6 - Other

Ex 6 - Other

I think Alex or likely anyone from the SCC group can update the Team on the NAS project.

Non-Responsive

That's all I can think of for now.

Thanks,
Elizabeth

From: Wolverton, Ann
Sent: Wednesday, August 26, 2015 9:23 AM
To: Bowen, Jennifer; Dockins, Chris; Evans, DavidA; Ferris, Ann; Garbaccio, Richard; Griffiths, Charles; Klemick, Heather; Kopits, Elizabeth; Marten, Alex; McGartland, Al; Moore, Chris; Newbold, Steve; Pasurka, Carl; Sargent, Keith; Shadbegian, Ron; Sheriff, Glenn; Simon, Nathalie; Simpson, David; Snyder, Brett
Subject: Climate team: Please send me agenda items by noon today. Thanks! (NT)

To: Shouse, Kate[Shouse.Kate@epa.gov]; Newbold, Steve[Newbold.Steve@epa.gov]; Griffiths, Charles[Griffiths.Charles@epa.gov]; Wolverton, Ann[Wolverton.Ann@epa.gov]
Cc: Marten, Alex[Marten.Alex@epa.gov]
From: Kopits, Elizabeth
Sent: Tue 8/25/2015 3:28:42 PM
Subject: FW: Inside EPA: EPA Uses Novel 'Social Cost Of Methane' In Landfill, Oil & Gas Proposals

Fyi -

From: Beauvais, Joel
Sent: Tuesday, August 25, 2015 9:06 AM
To: Rennert, Kevin; McGartland, Al; Marten, Alex; Kopits, Elizabeth
Subject: Inside EPA: EPA Uses Novel 'Social Cost Of Methane' In Landfill, Oil & Gas Proposals

ICYMI

EPA Uses Novel 'Social Cost Of Methane' In Landfill, Oil & Gas Proposals

Posted: August 24, 2015

EPA is using its novel "social cost of methane" (SCM) estimate to calculate the climate benefits of its newly proposed methane rules for landfills and the oil and gas sector, using values that are significantly larger than its similar -- and controversial -- carbon dioxide (CO2)-focused metric to calculate the bulk of the proposals' quantified benefits.

The agency has used the new values at least once before, to suggest potential co-benefits from reducing upstream and downstream methane emissions as a result of its proposed phase 2 fuel efficiency standards for medium- and heavy-duty trucks.

But use of the metric in the landfill and oil & gas proposals is significant because it marks the first time the agency has used the metric to quantify direct climate benefits of a regulation limiting methane, resulting in a cost-benefit calculation that accounts for nearly all of the rules' monetized benefits.

The values are pleasing environmentalists, who have long called for the

measures to help justify strict new climate rules that regulate methane, the greenhouse gas (GHG) that is significantly more potent than CO2. “It's good to see EPA undertaking a serious effort to value these pollution reductions,” one environmentalist says.

But they have already begun to attract criticism from at least one industry attorney who argues that the agency's new methane values suffer from many of the same flaws that afflict the administration's social cost of carbon (SCC) metric, including an insufficient discount rate, use of global, rather than only domestic, benefits, and a failure to subject the calculations to adequate peer review.

Wayne D'Angelo of the law firm Kelley Drye & Warren says in an Aug. 19 blog post that the agency's cost-benefit review of in its oil and gas new source performance standards (NSPS), which is based on its new SCM metric, is too uncertain to provide sufficient confidence in the rule's overall benefits.

“EPA offers both cost and benefit estimates 'give or take' about $100 million each. Importantly, EPA has good reason to doubt its benefits calculations in particular,” he writes. “EPA calculated future benefits using an estimate of the social cost of methane that has never before been used in rulemaking,” he says.

Like the administration's SCC, the agency's SCM monetizes the climate damages that are expected to result from each incremental ton of the gas that is released. As a result, the value can be used to quantify the benefits of rules that curb the gas and eventually limit climate-related damages from sea level rise and other adverse effects.

The CO2 values in the SCC have already been used in a host of EPA, Department of Energy and other agencies' rules that reduce GHG emissions, including the agency's final GHG rule for existing power plants, which uses the SCC to show $20 billion in climate benefits in 2030.

But the administration's development of the SCC has drawn strong criticism from industry officials and GOP lawmakers, who charge the figures overestimate the potential benefits of domestic policies in part by calculating global benefits, and because they are based on arbitrarily selected adverse climate impacts, use multiple highly uncertain variables and were not developed transparently.

More Potent

While the administration's current SCC value for CO2 emitted in 2025 is $48 per ton using a 3 percent discount rate, EPA estimates that an incremental ton of methane emissions released that same year would inflict a $1,500 cost to society, using a 3 percent discount rate.

The per-ton damage estimates for the SCM are higher than the SCC because methane is a much more potent GHG over the short term than CO2. The most recent estimates from the International Panel on Climate Change (IPCC) say methane is 28 to 36 times as potent as CO2 over 100 years, compared to an earlier estimate of 25 times as potent.

Using these SCM values, EPA says its recently proposed methane rules for new and existing landfills, as well as its NSPS for new and modified oil and gas drilling sources, yield up to $1.2 billion in combined climate benefits in 2025.

For landfills, EPA says the Aug. 14 proposed guidelines for existing facilities would yield about 440,000 metric tons of methane cuts in 2025, resulting in $660 million in benefits. That compares with a range of $35 million to $47 million in costs.

The Aug. 18 NSPS for the oil and gas sector, EPA says, would drive between 310,000 and 360,000 metric tons of emissions cuts, yielding between $460 million and $550 million in climate benefits. EPA estimates a range of $320 million to $420 million in costs.

In each case, the climate benefits tied to the SCM represent the vast majority of the proposal's quantified benefits.

EPA outlines its justification for the new SCM calculations in regulatory impact analyses (RIAs) for the landfill and oil and gas proposals.

The agency notes that it earlier used an “interim” methane valuation approach in two prior rules that converted methane emission cuts to CO2 equivalents using a global warming potential (GWP) calculation.

That approach was used in both a prior oil & gas NSPS targeting volatile organic compounds, promulgated in 2012, and the phase 2 light-duty vehicle GHG rule, which was also finalized in 2012.

But instead of including the GWP-based estimates in the main cost-benefit analysis for those rules, EPA included the figures only in “sensitivity” analyses.

Such figures are “not ideally suited for” cost-benefit reviews, EPA says, because methane exists over different time scales and is linked to different environmental and social impacts. For example, increased fertilization benefits from CO2 would be incorrectly attributed to methane in a GWP-based approach.

As such, EPA says the GWP-based approach likely underestimated methane-

related damages.

Environmental groups have earlier urged EPA to craft a cost estimate for methane releases, with the Environmental Defense Fund arguing in 2014 comments, for example, that the SCC is not suited for quantifying the costs of methane emissions.

'First Set' Of Values

The agency notes that since those 2012 rules were issued, Alex Marten, a researcher in EPA's National Center for Environmental Economics, and four co-authors published the first set of SCM “estimates in the peer-reviewed literature that are consistent with the modeling assumptions underlying” the SCC.

The figures in the Marten study reflect radiative forcing estimates from the fourth IPCC report, released in 2007. In that report, methane was estimated at 25 times more potent than CO2 over a 100-year time period.

EPA notes that IPCC's latest report, released in 2014 after the Marten study was developed, says methane is between 28 and 36 times as potent, reflecting changes to the lifetime and radiative estimates for CO2, changes to the lifetime estimate for methane and the effect of methane on “other climatically important substances such as tropospheric ozone and stratospheric water vapor.”

It is not clear whether the methane valuations used in the RIAs were updated with the IPCC's latest GWP estimates.

EPA in the RIAs says it “recently conducted a peer review of the application of the [Marten] non-CO2 social cost estimates in regulatory analysis and received responses that supported this application.”

The agency says two of three reviewers found it “appropriate” to use the figures in RIAs, and that all three reviewers encouraged improvements to both the SCC and the SCM.

Because the reviewers says the SCM is “generally consistent” with the SCC, which is supported by White House Office of Management & Budget (OMB) guidance, that “leads EPA to conclude that use of the [SCM] estimates is an analytical improvement over excluding methane emissions from the monetized portion of benefit cost analysis.”

EPA adds that it is seeking comment on the use of the estimates in the RIAs.

Dueling Views

The environmentalist notes that the SCM builds upon the approach used to develop the SCC, and that its approach of directly modeling the impacts of methane is “perhaps a more rigorous and up-to-date look at the impacts” than earlier efforts on the issue.

“It's very important to have a very rigorous assessment of the range of benefits that are associated with reducing that particular pollutant,” the source says.

But D'Angelo charges that the SCM estimates suffer from many of the same flaws as the SCC values.

They were “seemingly never peer reviewed,” he says in his blog post. “In the last few months, EPA apparently conducted its own peer review of the Agency's use of the study to model benefits from the Oil and Gas NSPS, but never identified the peer reviewers,” he says.

D'Angelo adds that EPA also did not provide “any meaningful opportunity to comment” on the SCM, and that discussion of a potential future methane metric in the light-duty vehicle rule was a poor venue for such comment.

He also faults EPA's failure to use both 7 percent and 3 percent discount rates as suggested by OMB guidance, and that both the methane and CO2 estimates rely on global benefits instead of only domestic benefits.

Under the cost-benefit reviews, he says, “The benefits appear larger than the costs, but the costs are borne by the U.S. economy alone, while the benefits are shared with every other country in the world.”

In a July 6 formal response to comments document, the administration defends its decision not to include a 7 percent discount rate in the SCC, as well as to look at global benefits. After considering the comments, the administration says, it continues to recommend use of the SCC in cost-benefit reviews because it represents “the best scientific information on the impacts of climate change available in a form appropriate” for RIAs. -- *Lee Logan* (llogan@iwpnews.com)

Related News | Mid Day E-mail | Air | Climate Policy Watch | Energy | Natural Gas |

184205

To: Snyder, Brett[Snyder.Brett@epa.gov]; Bowen, Jennifer[Bowen.Jennifer@epa.gov]
From: Kopits, Elizabeth
Sent: Mon 8/24/2015 4:47:51 PM
Subject: RE: REVISED: Call for Agenda topics for NCEE Update Meeting with Joel

Thanks!

From: Snyder, Brett
Sent: Monday, August 24, 2015 12:47 PM
To: Kopits, Elizabeth; Bowen, Jennifer
Subject: FW: REVISED: Call for Agenda topics for NCEE Update Meeting with Joel

Hi – they will be added to the agenda.

Thanks,

Brett

From: McGartland, Al
Sent: Monday, August 24, 2015 12:44 PM
To: Snyder, Brett
Cc: Bowen, Jennifer
Subject: Re: REVISED: Call for Agenda topics for NCEE Update Meeting with Joel

Yep. I should have been clear that you should ask folks for their ideas as well. These are good ones to add.

Sent from my iPhone

On Aug 24, 2015, at 12:39 PM, Snyder, Brett <Snyder.Brett@epa.gov> wrote:

Hi Al – Elizabeth suggested these in addition to the list you started this morning.

Would you like to add them?

Brett

566-2261

From: Kopits, Elizabeth
Sent: Monday, August 24, 2015 12:29 PM
To: Snyder, Brett
Cc: Bowen, Jennifer
Subject: RE: REVISED: Call for Agenda topics for NCEE Update Meeting with Joel

Hi Brett,

If there is room, can you please add the following to the agenda for tomorrow's meeting? Both should be short.

Non-Responsive

SCC/SCM – update on NAS project, update to EPA SCC website

Thanks!

Elizabeth

From: Simon, Nathalie
Sent: Wednesday, August 19, 2015 10:31 AM
To: OP-NCEE-Everyone
Subject: REVISED: Call for Agenda topics for NCEE Update Meeting with Joel

Please send your suggested agenda items for next week's biweekly with Joel to **Brett by noon on Monday August 24th.**

Thanks!

Nathalie

From: Simon, Nathalie
Sent: Tuesday, August 18, 2015 3:09 PM
To: OP-NCEE-Everyone
Subject: Call for Agenda topics for NCEE Update Meeting with Joel

Hi everyone—

Our next Update meeting with Joel is scheduled for August 25th at 10:00.

Since I will be out of the office starting this Friday, please send any agenda topics you might have to Jenny by **noon on Monday August 24th**.

Thanks!
Nathalie

To: Marten, Alex[Marten.Alex@epa.gov]
From: Kopits, Elizabeth
Sent: Wed 8/19/2015 2:17:24 PM
Subject: FW: Social Cost of Carbon/Methane Update

See Christian's question below. Have we talked through this before?

In the paper we talk about why the GDP declines for lower discount rates – i.e., the relatively shorter atmospheric lifetime leads to a situation where lowering the discount rate has a greater impact on the SC-CO2 than the SC-CH4 - but not so much about why it would end up being lower than the GWP, or why the 95th 3% CH4 GDP would be lower than the mean 3% CH4 GDP. In PAGE, is it just that a high draw of some uncertain parameter has a disproportionately larger effect on SC-CO2 than SC-CH4 due to differences in lifetime of each gas? Or is it related to the large time step? The 95th 3% CH4 GDP estimates are lower than the mean 3% estimates for FUND too, but they never get lower than the GWP - likely because of significant CO2 fertilization effect included in the SC-CO2. In DICE, the 95th 3% CH4 GDP always remains higher than mean 3% CH4 GDP. Why is this? Is it because the only uncertain parameter is ECS?

Although he doesn't ask about it below, the mean 2.5% CH4 GDP estimates for both DICE and PAGE are also lower than the GWP.

Thoughts?

From: Michaud,Christian [NCR] [mailto:Christian.Michaud@ec.gc.ca]
Sent: Wednesday, August 19, 2015 9:07 AM
To: Kopits, Elizabeth
Subject: RE: Social Cost of Carbon/Methane Update

Hi Elizabeth,

I'm doing very good and I hope you are too. Thanks for this, it is very helpful to keep tabs on how things are moving forward on your end! I had noticed the oil & gas rule, given that it is a high profile regulation that got media attention, but hadn't seen the one for landfills just yet.

I also meant to email you as I had a question about the 95th percentile estimates for the SC-CH4 (probably the SC-N2O as well, but I haven't looked into this particular question for N2O yet). While I was comparing the 95th percentile estimates with the GWP approach, I noticed that early estimates in DICE and PAGE were lower than the GWP approach. Did you notice this as well?

I see that the 95th percentile which include all 3 models were always higher for the SC-CH4 than with the GWP approach, so you may not have noticed, but since we remove FUND from our 95th percentile estimates, this pattern was very noticeable. Do you have an idea of what may explain this counterintuitive result? I have some ideas of what may be going on, but would be very interested in hearing from you about this.

Thanks again!

Christian Michaud

819-956-5146

From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: August 19, 2015 8:40 AM
To: Michaud,Christian [NCR]
Subject: RE: Social Cost of Carbon/Methane Update

Hi Christian,

I hope all is well. To follow up on our conversation from a few weeks ago, I just wanted to let you know, in case you haven't seen it yet, that EPA recently released 2 rules with methane impacts - Landfills (http://www.epa.gov/ttn/atw/landfill/landflpg.html) and Oil&Gas (http://www.epa.gov/airquality/oilandgas/actions.html). In both rules, benefits from methane reductions are quantified using the Marten et al. estimates.

Regards,

Elizabeth

From: Marten, Alex
Sent: Thursday, July 23, 2015 9:57 AM
To: Michaud,Christian [NCR]
Cc: Kopits, Elizabeth; McGartland, Al
Subject: Re: Social Cost of Carbon/Methane Update

Great!

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

On Jul 23, 2015, at 9:56 AM, Michaud,Christian [NCR] <Christian.Michaud@ec.gc.ca> wrote:

Hi Alex,

Thank you very much for taking the time to reduce the size of the file for us to be able to receive it. I've inspected both spreadsheets, and I can confirm that the 10,000 simulations are there for all runs now.

Best Regards,

Christian Michaud

819-956-5146

From: Marten, Alex [mailto:Marten.Alex@epa.gov]
Sent: July 23, 2015 9:52 AM
To: Michaud,Christian [NCR]; Kopits, Elizabeth
Cc: McGartland, Al
Subject: RE: Social Cost of Carbon/Methane Update

[Part 2/2 - N2O Only]

Hi Christian,

I am sorry about that, I'm not sure how that happened. I have recompressed the file and attached it to this email. Hopefully this version will contain results for all 10,000 simulations when extracted.

My first couple of attempts were rejected by the CA server because the file was too large, I have reduced the number of decimal places included in the results to reduce the size of the file. Hopefully this one goes through.

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Michaud,Christian [NCR] [mailto:Christian.Michaud@ec.gc.ca]
Sent: Thursday, July 23, 2015 8:51 AM
To: Kopits, Elizabeth
Cc: Marten, Alex; McGartland, Al
Subject: RE: Social Cost of Carbon/Methane Update

Hi Elizabeth,

Thank you very much, this is very helpful.

I just had a question with regards to the model output from the SCCH4/SCN2O runs. It seems that there are fewer simulations in this run that the one undertaken for the SCCO2. I noticed that in the numbers besides the estimates, the file contains the estimates numbered 1 through 49, and 4924 through 10000. Is it possible that compressing the file has removed some data points, or was this intended?

Thanks again,

Christian Michaud

819-956-5146

From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: July 22, 2015 10:21 PM
To: Michaud,Christian [NCR]
Cc: Marten, Alex; McGartland, Al
Subject: Fw: Social Cost of Carbon/Methane Update

Hi Christian - Per my previous message, here is the 2nd of the two emails containing the files you requested. Please let me know if you have any trouble with it.

Thanks,

Elizabeth

From: Kopits, Elizabeth
Sent: Wednesday, July 22, 2015 10:16 PM
To: Michaud,Christian [NCR]
Cc: McGartland, Al; Marten, Alex
Subject: Fw: Social Cost of Carbon/Methane Update

Hi Christian,

It was great to talk to you and Chris and Warren this morning. Thank you again for reaching out. Per your request, attached here are: the raw output for the July 2015 SCC estimates, the raw output for Marten et al. (corrected version that reflects the 2 minor revisions in the July 2015 SCC TSD), and a copy of the Marten et

al. (2014) paper. The corrigendum for the paper that explains the 2 minor revisions should be published by the journal tomorrow, so we will send that along shortly thereafter.

I hope this helps for now. Please let me know if you have any trouble with the files or if you have any technical questions on the Marten et al. paper methodology.

Best wishes,

Elizabeth

From: Marten, Alex
Sent: Wednesday, July 22, 2015 2:39 PM
To: Kopits, Elizabeth
Subject: RE: Social Cost of Carbon/Methane Update

The corrigendum will be published tomorrow, so I can't attach that. We can send tomorrow though.

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Michaud,Christian [NCR] <Christian.Michaud@ec.gc.ca>
Sent: Wednesday, July 22, 2015 10:18 AM
To: McGartland, Al; Kopits, Elizabeth

Subject: RE: Social Cost of Carbon/Methane Update

Apologies, this conference number is not on the same line, the call-in number is Conference code
Conference code

Christian Michaud

819-956-5146

From: McGartland, Al [mailto:McGartland.Al@epa.gov]
Sent: July 22, 2015 10:16 AM
To: Michaud,Christian [NCR]; Kopits, Elizabeth
Subject: RE: Social Cost of Carbon/Methane Update

The phone gods are telling me that the conference id Conference code s not valid. Waiting on operator.

From: Michaud,Christian [NCR] [mailto:Christian.Michaud@ec.gc.ca]
Sent: Wednesday, July 22, 2015 10:14 AM
To: Kopits, Elizabeth
Cc: McGartland, Al
Subject: RE: Social Cost of Carbon/Methane Update

For some reason, we are having problems with this number, could you call in at Conference code
Conference code

Talk to you in a bit.

Christian Michaud

819-956-5146

From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: July 22, 2015 10:11 AM
To: Michaud,Christian [NCR]
Cc: McGartland, Al
Subject: Re: Social Cost of Carbon/Methane Update

No problem. If it doesn't work, let us know if we should try a different number.

From: Michaud,Christian [NCR] <Christian.Michaud@ec.gc.ca>
Sent: Wednesday, July 22, 2015 10:10 AM
To: Kopits, Elizabeth
Subject: RE: Social Cost of Carbon/Methane Update

Hi Elizabeth,

We were waiting on the line, but we may have used the wrong one. I'll double check that we called in to the same number. Apologies for the delay.

Christian Michaud

819-956-5146

From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: July 22, 2015 10:08 AM
To: Michaud,Christian [NCR]
Cc: McGartland, Al
Subject: Re: Social Cost of Carbon/Methane Update

Hi Christian,

Can you still talk now? I called in to the number below but it says the

moderator has not yet joined so I am on hold.

Thanks,

Elizabeth

From: Michaud,Christian [NCR] <Christian.Michaud@ec.gc.ca>
Sent: Wednesday, July 15, 2015 10:13 AM
To: Kopits, Elizabeth
Subject: RE: Social Cost of Carbon/Methane Update

Hi Elizabeth,

Next Wednesday at 10-10:30AM sounds good for us. We do have a conference call line. Here is the call-in info:

Dial-in number: **Conference code**

Conference ID: **Conference code**

Thanks,

Christian Michaud

819-956-5146

From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: July 15, 2015 9:13 AM
To: Michaud,Christian [NCR]
Subject: RE: Social Cost of Carbon/Methane Update

Hi Christian,

Let's say 10-10:30AM next Wednesday the 22nd. I think it might be easiest for us to use a conference call line because my boss, Al McGartland, will likely be joining as well and I will likely be working remotely that day. If you don't have one handy, I am happy to send a call-in number we can use.

Thanks,
Elizabeth

From: Michaud,Christian [NCR] [mailto:Christian.Michaud@ec.gc.ca]
Sent: Tuesday, July 14, 2015 4:12 PM
To: Kopits, Elizabeth
Subject: RE: Social Cost of Carbon/Methane Update

Hi Elizabeth,

Thank you very much for your quick response.

I hadn't seen the OMB blog on the update, but I have learned through other news outlets about the response to public comments, revisions to the TSD as well as the NAS peer-review process. I have reviewed the updated Technical Update paper and shared the information with my Chris and Warren, so we do have an understanding of what was changed in the methodology. With that said, I will review the post of the blog to ensure that I didn't miss anything on this.

As for timing of the call, it seems like all of us would be available on Wednesday the 22nd between 10 AM and 11 AM, and Thursday the 23rd between 1 PM and 2 PM. Would there be a half-hour time slot that would work for you at those times?

Best regards,

Christian Michaud

819-956-5146

From: Kopits, Elizabeth [mailto:Kopits.Elizabeth@epa.gov]
Sent: July 14, 2015 4:00 PM
To: Michaud,Christian [NCR]
Subject: Re: Social Cost of Carbon/Methane Update

Hi Christian,

Yes I would happy to talk any time. Next week either Wednesday or Thursday would be best. This week would be fine too.

In the meantime have you seen the 7/2 OMB blog post on SCC? It summarizes the latest developments and provides links to the new files.

Please feel free to suggest a couple of times that might work on your end. Looking forward to speaking soon.

Regards,

Elizabeth

Sent from my iPhone

On Jul 14, 2015, at 3:40 PM, "Michaud,Christian [NCR]" <Christian.Michaud@ec.gc.ca> wrote:

> Hello Elizabeth,
>
> My name is Christian Michaud from the Economic Analysis Directorate at Environment Canada. Previously, I worked under John Cuddihy, who was in

touch with you about developments around the Social Cost of Carbon. As he left on an assignment recently, I've been asked to take over the lead on this file.

Recently, we have seen quite a few developments around the SCCO2 and SCCH4, and were wondering whether it would be possible for my new director, Warren Goodlet, my manager, Chris Adams, and myself to have a quick chat with you sometime next week in order to have a better understanding of what might be expected in the next few months on those files.

Please let me know if that would work for you.

Best regards,

Christian Michaud
Economist | Économiste
Economic Analysis Directorate | Direction de l'analyse économique

Strategic Policy Branch | Direction générale de la politique stratégique
Environment Canada | Environnement Canada
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Facsimile | Télécopieur 819-953-3241
Government of Canada | Gouvernement du Canada
Website | Site Web www.ec.gc.ca

To: Marten, Alex[Marten.Alex@epa.gov]
From: Kopits, Elizabeth
Sent: Tue 8/18/2015 8:14:46 PM
Subject: Re: how about something like this?

Good point. Thanks!

Sent from my iPhone

On Aug 18, 2015, at 3:56 PM, "Marten, Alex" <Marten.Alex@epa.gov> wrote:

I think this makes sense. I had two small edits below including changing the expected number of slides on the charge from 5-7 to 4-5. It may expand, but better to aim low and miss high.

--

Alex L. Marten
phone: (202) 566-2301
email: marten.alex@epa.gov

From: Kopits, Elizabeth
Sent: Tuesday, August 18, 2015 3:54 PM
To: Marten, Alex
Subject: how about something like this?

Still very rough – but just want to get the basic outline out there –

Intro (3-4 slides)

- Rigorous evaluation of benefits and costs has been a core tenet of the Federal rulemaking process for decades. …

- History –

o estimates of SCC have been published in the academic literature for many years, since…; started being used in regulatory analysis following 2007 court case

o Obama administration brought consistency to values being used by agencies – issued estimates developed by an interagency working group in 2010, updated these in 2013 to reflect new versions of the models

- Process used to develop the estimates has involved many opportunities for public input

o Via agency rulemakings and through separate OMB public comment period. (also somehow weave in GAO review conclusions)

o Commenters offered a wide range of perspectives on the process, methodology, and results, and varied in the level of specificity for potential opportunities to improve particular aspects of the SCC methodology in future updates.

- To help synthesize the technical information and input reflected in the comments, we are seeking your independent expert advice on how to approach future updates. Asking you to

o review the latest research on modeling the economic impacts of climate change to help inform future updates to the SCC estimates used in Federal regulatory impact analyses.

o and provide recommendations on the merits of different technical approaches for modeling and highlight research priorities going forward.

Charge questions (4-5 slides) – general overview of 2 part charge, and brief overview of each category of charge questions

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.

/s/ Miyoko Sakashita
Miyoko Sakashita, Oceans Director
Center for Biological Diversity
1212 Broadway #800
Oakland, CA 94612
(510) 844-7100
miyoko@biologicaldiversity.org

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

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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).

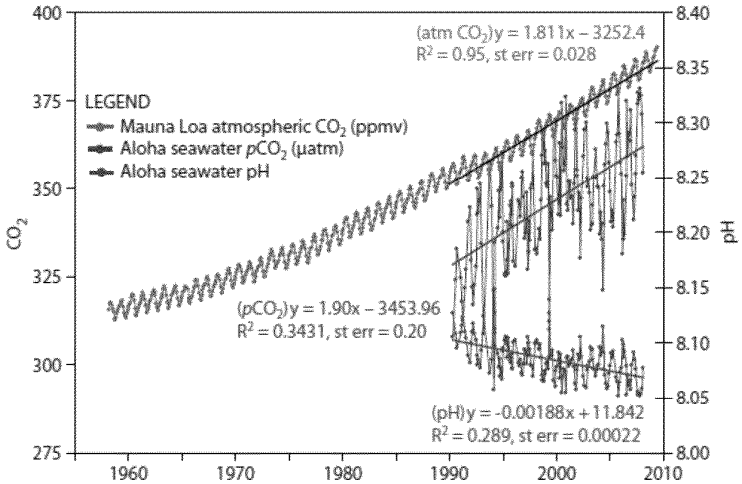

Figure 1. Time series of atmospheric CO 2 at Mauna Loa (ppmv) and surface ocean pH and pCO2 (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean (see inset map). Note that the increase in oceanic CO 2 over the period of observations is consistent with the atmospheric increase within the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

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).

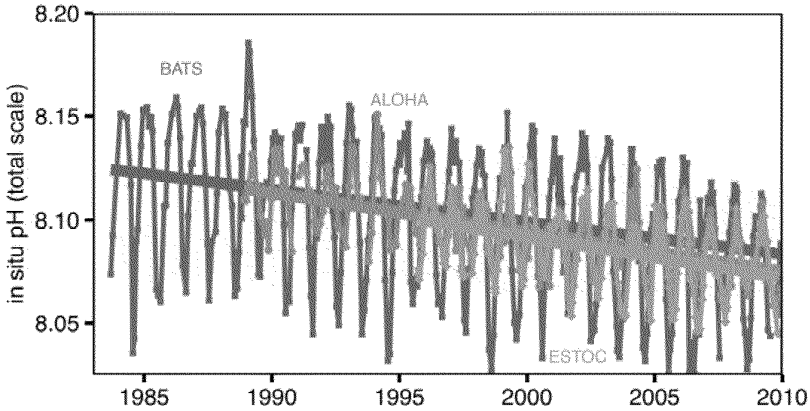

Figure 2. Long-term trends of surface seawater pH at three subtropical ocean time series in the North Atlantic and North Pacific Oceans, including (a) Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; green) and Hydrostation S (32°10', 64°30'W) from 1983 to present (updated from Bates, 2007); (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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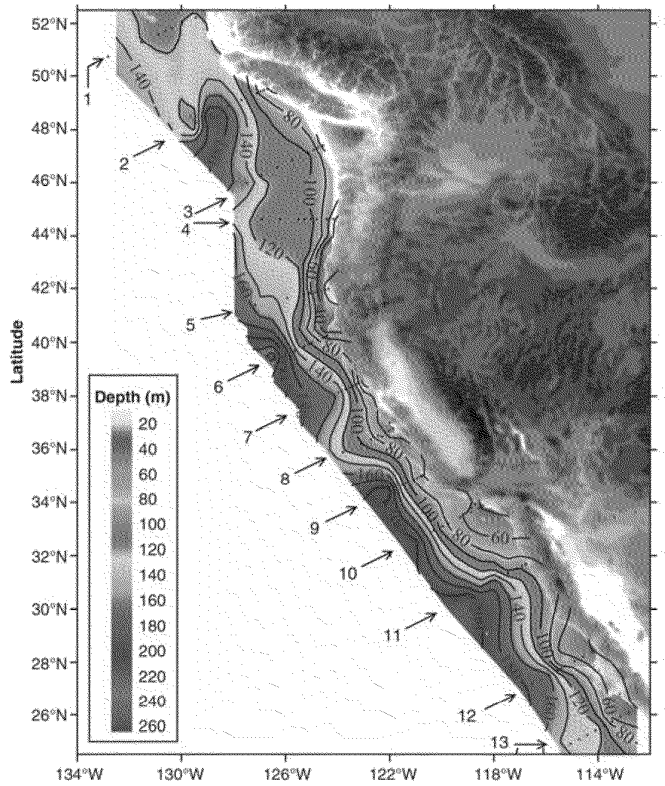

Figure 3. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada, to San Gregorio Baja California Sur,Mexico. On transect line 5, the corrosive water reaches all the way to the 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.

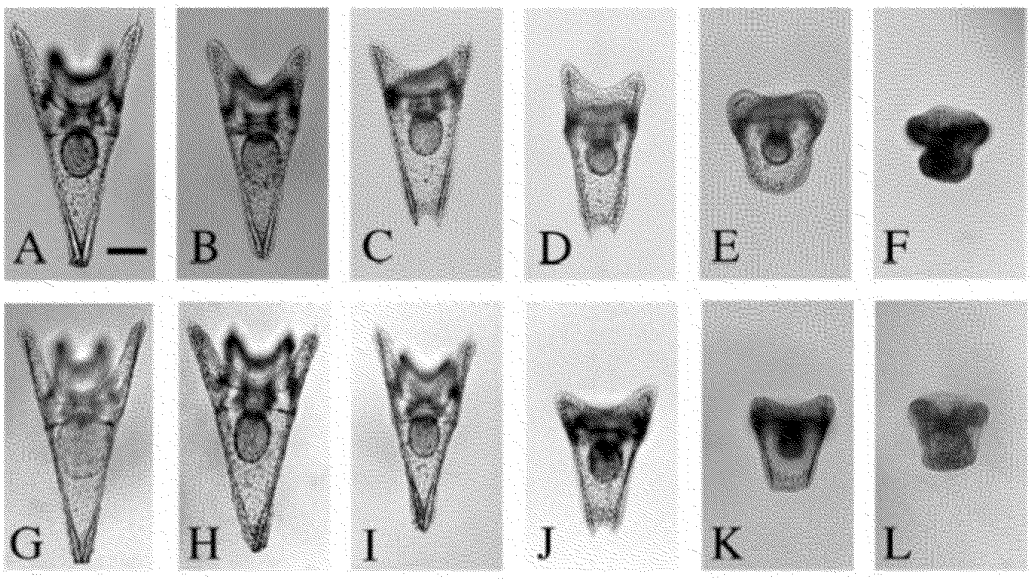

Fig. 6. *Hemicentrotus pulcherrimus*. Morphology of 4-armed pluteus larvae cultured for 3 d in (A–F) CO_2-seawater and (G–L) HCl-seawater. (A & G) control (pH 8.0); (B & H) +500 ppm (pH 7.8); (C & I) +1000 ppm (pH 7.6); (D & J) +2000 ppm (pH 7.4); (E & K) +5000 ppm (pH 7.0); (F & L) +10 000 ppm (pH 6.8).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

(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

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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June 30, 2015

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Re: Supplement to the Petition for Rulemaking Pursuant to section 21 of the Toxic Substances Control Act, 15 U.S.C. 2620, Concerning the Regulation of Carbon Dioxide

Dear Administrator McCarthy,

On June 30, 2015, the Environmental Protection Agency (EPA) received a petition to regulate carbon dioxide (CO_2) from cradle to grave under section 6 of the Toxic Substances Control Act (TSCA) or in the alternative to develop a testing rule for CO_2. The petition provides information concerning the devastating risk to the marine environment and wildlife, and risk to human health from ocean acidification. Accordingly, EPA must make a determination as to whether CO_2 presents or may present an unreasonable risk of injury to the environment or human health due to the severe environmental consequences of ocean acidification. As a cosigner of that petition, I submit this supplement to the petition under my signature.

US EPA section 21 guidance states: "The key findings relating to unreasonable risk must be made both when a new regulation is proposed, and when an existing regulation is amended or repealed. Petitioners should provide data to support these finds." This supplement provides additional information supporting the unreasonable risk find. I respectfully request that EPA consider the data and information provided in this supplement to the petition in making its determination on our petition.

Petitioners demonstrated that the acidification of the open ocean has a single cause but multiple effects. That the decreasing ocean pH is being inexorably driven by the increase in the atmospheric concentration of carbon dioxide from anthropogenic emissions and is the incontrovertible result of the second law of thermodynamics. That this physical and chemical dynamic has been observed, monitored, documented, and is straightforward to predict into the future. [1] That it has many harmful effects on the ecology of the ocean, some of the harmful effects are well established, others lack conclusive information or are more speculative. Many of these are significant

[1]Caldeira and Wickett, Nature 425, 2003 and Journal of Geophysical Research 110, 2005; Orr et al. 2005 Nature 437; Raven et al. 2005 ,The Royal Society.

effects, and some could be catastrophic. That these harmful effects are exacerbated in near shore areas by NOx and SOx emissions, runoff, temperature rise and other effects.[2]

Climate Impacts

According to scientific experts: "Reducing CO_2 emissions is the only way to minimise [sic] long-term, large-scale risks" (IBGP et al. 2013). So any abatement will by necessity also abate Climate change disamenities.

Under TSCA the reasonableness of the risk depends on whether the costs of the ecological and health disamenities outweigh the benefits from mitigation, minus the costs of mitigation. To the extent possible the costs and benefits must be quantified to make this determination. According to USEPA Benefit Assessment Guidelines action to mitigate ocean acidification would be classified as a "significant regulatory action" ...the ... " economic analysis of regulatory or policy options should present all identifiable costs and benefits that are incremental to the regulation or policy under consideration. These should include directly intended effects and associated costs, as well as ancillary (or co-) benefits and costs."

In EPA regulations, ancillary benefits can be much larger than direct benefits. (For example, Agency regulations to control NOx emissions are premised on the enormous ancillary particulate matter and ozone reduction benefits that result indirectly from the NOx reduction and control). This is also the case for ocean acidification (Although ocean acidification mitigation has enormous human health and environmental benefits in it's own right). Mitigation options for ocean acidification have by necessity the ancillary effect of slowing global temperature rise and preventing the disamenities associated with a global rise in temperature. Therefore this supplement presents both ocean acidification and climate information relevant to the reasonable risk finding.

Mitigation Under TSCA Includes Sequestration of Legacy Carbon

While current emissions may be the immediate cause of the increase in ocean acidification, past emissions are the proximate cause. The oceans have absorbed from about a third of the 500 plus billion tons of past or legacy carbon emissions, lessening Climate impact. However, these emissions have eroded, i.e., "used up" the buffering capacity of the oceans. This buffering capacity is what keeps ocean pH in a narrow, bio-friendly range. As the buffering capacity lessens, smaller and smaller amounts of CO_2 will result in larger and larger decreases in pH. The absorption by the ocean of legacy emissions over the past decades have caused the rapid current decrease in pH and have made the projected future decrease in pH to carbonate unsaturation levels possible, and have caused it to accelerate. Since legacy emissions are the proximate cause of both the current level and the acceleration in the decrease in pH, these emissions must be part of the design and funding of any remedy, or an undue burden is placed on the current emitters to remedy the damage caused by past emitters. The courts have held, e.g., in CERCLA cases that requirements stemming from past actions (which were legal at the time) isn't retroactive, but rather a reimbursement obligation.[3]

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[2]Duarte et al. Coastal and Estuarine Research Federation 2013
[3] UNITED STATES v. MONSANTO COMPANY, 858 F.2d 160 (4th Cir. 1988)

Again, the oceans absorb about a third of the anthropogenic emissions. This means that for decades rent seekers have extracted the benefits of fossil energy without paying for the environmental damages of the carbon emission, including the loss of the buffering capacity of the ocean and the attendant damages from ocean acidification. This is a classic "tragedy of the commons" situation. EPA has a long standing tradition and policy of making the polluter pay for environmental injury. Petitioner asks that both legacy and current emissions be included in determining the remedies and who must comply, based on the contributory proportion to the harm from ocean acidification, using, for example, the Emission Inventory. (The Agency has the authority to ignore small emitters when transactional costs of including them are too large)

CO_2 Poses an Unreasonable Risk to Human Health

Petitioner asks the Agency to consider not only the well documented health effects from climate change[4] discussed in the petition but also the direct health impact from ocean acidification. Some of these are very significant and can be quantified.

The body of the petition cites increased mortality and morbidity from loss of fisheries and declines in marine based diets. These human health effects are in addition to the increased toxicity of algal blooms mentioned in the body of the petition, which can cause paralytic shellfish poisoning in humans. The loss of fisheries from ocean acidification, and the resultant scarcity of seafood also has significant human health impacts. For example, in a Harvard School of Public Health comprehensive analysis of fish and health, combining the evidence for major health effects of omega-3 fatty acids, while accounting for the health risks of mercury, and health risks of PCBs and dioxins in both adults and infants/ young children: results show that the benefits of eating a modest amount of fish per week--about 3 ounces of farmed salmon or 6 ounces of mackerel--reduced the risk of death from coronary heart disease (CHD) by 36%. By combining results of randomized clinical trials, the investigators also demonstrated that intake of fish or fish oil reduces total mortality--deaths from any causes--by 17%. [5]

USEPA consumption surveys find that about 10% of the US population consumes at least enough fish to garner the benefit.[6] Depending on price elasticity of demand this could translate into up to half a million premature deaths/year from loss of fisheries and the resultant scarcity of seafood.[7] In addition, increase in seafood prices will result in a loss of consumer surplus. Petitioner asks that the Agency develop a deterministic or a probabilistic assessment to quantify mortality and morbidity from the decreased availability and consumption of seafood that would result from ocean acidification fishery damage, as mentioned in the body of the petition (e.g., effects on salmon from plankton impacts). This will help the risk assessment to capture this significant human health impact as required in EPA's Benefit Assessment Guidelines.

There are also indirect effects and economic consequences, which after consideration of the effect on the national economy, small business, technological innovation, the environment, and

[4] National Climate Assessment, U.S. Global Change Research Program, 2014
[5] JAMA. 2006;296(15):1885-1899;]
[6] Estimated Per Capita Fish Consumption in the United States, USEPA August 2002
[7] Am J Public Health. 2010 February; 100(2): 216–222

public health as required under TSCA, are reasonably ascertainable.[8] These include other effects on Fisheries. It is probable that wild catch seafood loss, at least in part, will be replaced by aquaculture (currently about half of the world's seafood is farmed[9]). Farmed fish are fed fishmeal, soy and grain. It has been well established that fisheries have and will be increasingly negatively affected by ocean acidification. This will cause scarcities of fishmeal, both driving up the price of farmed fish (and negatively affecting consumption) and causing more reliance on grain and soy.

The substitution of grain and soy for fishmeal, and the additional amounts of grain and soy needed for the increased farmed fish to replace the decreasing availability of wild catch may itself result in increased cost and, in some cases substitution may not be not possible due to grain and soy yield limitations. A recent Nature Communication article [10] shows robust evidence of yield plateaus due to biophysical limitations for rice, wheat and maize, which together account for ~85% of global cereal production and contribute a majority of human calories eaten directly as staple foods, or indirectly through consumption of livestock fed with grain. Seafood accounts for about 15% of the global dietary protein from animal sources. Both farmed seafood and livestock will be stressed by the plateauing grain yields.

Aside from increasing demand, grain costs will also increase due to greater input requirements[11] as marginal lands are brought into production to keep up with the increased demand. This demand and cost increase will be exacerbated by population growth, currently changing global increases in dietary animal protein, and increased labor costs from the fine tuning of many different facets of management in the production system required to increase or maintain yields.

Another factor to be considered is the dietary exposure effect of using increased soy and grain for aquaculture. The Food Quality Protection Act (FQPA) requires EPA to assess the cumulative risks of pesticides that share a common mechanism when developing tolerances. EPA has issued guidance relative to assessing that risk.[12] [13] Pesticides with common mechanisms (organophosphates (OPs), N-methy carbamates, triazines, chloroacetanides, pyrethrins/pyrethroids) all have grain and soy tolerances. This will change cumulative exposure, and under FQPA requirements EPA must reassess tolerances if these exposure pathways become larger contributors. Additionally, the metabolic pathways for the degradation products will have to be determined if they are different for aquatic species.

Petitioner requests EPA address this through its FIFRA information gathering authority and tolerance reassessment program, or explain why it's not necessary to do so. Petitioner asks that the additional exposure and risk be shared with the public if tolerances are maintained at current levels, and that these risks to human health be included in the benefits assessment. If tolerances are

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[8] TSCA section 6(c) 4
[9] State of the World Fisheries and Aquaculture, FAO, 2010
[10] Nature Communications 4, Article number: 2918 doi:10.1038
[11] CGIAR Research Priorities for Marginal Lands. FAO 1997
[12] General Principles For Performing Aggregate Exposure And Risk Assessments USEPA, 2001
[13] Guidance on Cumulative Risk Assessment of Pesticide Chemicals That Have a Common Mechanism of Toxicity. Office of Pesticide Programs, USEPA 2002

lowered, petitioner asks that any costs to growers or loss of consumer surplus be also included in the assessment.

As FQPA requires local effects be considered, USEPA should consider whether farm location relative to runoff of these pesticides need be considered in the assessment, perhaps using the monitoring protocols and mathematical models that OPP typically relies on to generate exposure estimates for water quality assessments. As more of the US population become locovores[14], local fish farming and local crops may expose special populations to increased cumulative risk.

Executive Order 12898 requires that "each Federal agency shall make achieving environmental justice part of its mission by identifying and addressing, as appropriate, disproportionately high and adverse human health or environmental effects of its programs, policies, and activities on minority populations and low-income populations". EPA's Framework for Human Health Risk Assessment to Inform Decision Making[15] recommends including social considerations and environmental justice in informing decisions on risk. In addition, under either NEPA's (National Environmental Policy Act) guidance or TSCA's "functional equivalence"[16] the analyses should consider the effects on a community by addressing the full range of consequences of a proposed action as well as other environmental stresses which may be affecting the community, including diets, or differential patterns of consumption of natural resources, which may suggest increased exposures to environmental pathways presenting potential health risk. To comply with these goals petitioner asks that EPA consider the Environmental Justice implications of whether the increased cost of seafood high in omega-3's will result in a more unhealthy ratio of omega-3 to omega-6 oils in certain low income communities. This ratio has been shown to be an important driver in mortality and morbidity studies.

Petitioner asks that the Agency consider the net effect on diet from ocean acidification and include the expected morbidity and mortality from all the changes in diet described above.

Market Failure

Petitioner endorses the President's Counsel of Economic Advisors' statement that "The emission of greenhouse gases such as carbon dioxide (CO_2) harms others in a way that is not reflected in the price of carbon-based, energy, i.e., CO_2 emissions create a negative externality. Because the price of carbon-based, energy does not reflect the full cost or economic damages, of CO_2 emissions, market forces result in a level of CO_2 emissions that is too high. Because of this market failure, public policies are needed to reduce CO_2 emissions and thereby limit the damage to economies and the natural world from further climate change."[17] One of these "harms" is Ocean Acidification. The petition and the options presented herein provide vehicles for implementing the public policy called for by the Counsel necessary to rectify the market failure.

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[14] R.E. Galt Counting and Mapping Community Supported Agriculture, ACME: An International E-Journal for Critical Geographies, 2011, 10 (2), 131 - 162

[15] Framework for Human Health Risk Assessment to Inform Decision Making, April 5, 2014, U.S. Environmental Protection Agency

[16] 489 F.2d 1247 (D.C. Cir. 1973).

[17] The Cost of Delaying Action to Stem Climate Change, CEA, July 2014.

Emission Reduction *and* Sequestration

Given the magnitude of the ocean acidification problem, the mitigation prescription to address this market failure must also be large. Nature maintains carbon dioxide atmospheric concentrations within a narrow band, by balancing emissions with sequestration. Nature efficiently removes atmospheric carbon by transforming it into biomass and minerals, or "storing" it in the oceans (the source of the ocean acidification problem). Unlike the natural cycle which is in dynamic equilibrium, the anthropogenic carbon cycle is not in equilibrium and is unbalanced. Man takes Gigatons of fossil carbon and puts it in the air, but takes very little back. In excess of a third of this increase in atmospheric carbon ends up in the ocean and lowers the ocean pH. The economics of the anthropogenic carbon cycle don't take in account the externalities of ocean acidification (or climate change) so the economic carbon cycle is skewed towards emissions and away from sequestration. While the amount of the imbalance is relatively small when compared to the annual amount of carbon nature moves into and out of the atmosphere, it is consistently biased in one direction and over the years has almost doubled the baseline atmospheric carbon.

While the Administration has not directly attempted to regulate ocean acidification it has attempted to reduce carbon emissions because of Climate considerations. The Administration's recent Climate Initiative and in fact, almost all of USEPA's climate and carbon initiatives to date, are and have focused on reducing emissions. Almost none of the efforts focus on sequestering carbon. Petitioner stresses that the carbon cycle can't presently be balanced by reducing emissions only, since, in the foreseeable future, there will continue to be a large net bias towards carbon emissions over carbon removal stemming from increasing energy demand, as well as wealth and population effects and the fossil fuel requirements of the extant energy infrastructure. (Petitioner observes that if you can't turn a sink faucet off, then you must open the drain to avoid an overflow…our energy infrastructure is a "faucet" and sequestration can be the "drain")

This is a market failure, because the environmental cost of emissions is not included in the price of energy, and therefore the environmental benefit of sequestration is not valued. Petitioner recommends that the Agency include options in the cost analysis that can significantly affect this bias, i.e., options which sequester carbon as well as options which reduce emissions. In any case, in order to determine if a risk is unreasonable under TSCA, the Agency must determine the efficacy, efficiency and supply function of all significant mitigation remedies.

Remedies

Determining whether a risk is unreasonable under TSCA is a function of government. However, as the Agency's Petition Guidance points out, petitioners have an obligation to present as much information as possible, e.g, to identify relevant aspects of the unreasonable risk determination and demonstrate that these aspects are knowable. Petitioner believes the Agency is both knowledgeable and active concerning carbon emission reduction, but less well versed and less active in sequestration. It's beyond the petitioner's responsibility and ability to provide an exhaustive, quantitative list of sequestration options. Rather examples are provided herein to demonstrate that sequestration opportunities to offset both legacy carbon and current emissions exist. The list is limited and not meant to be definitive of sequestration opportunities.

TSCA requires that the Agency consider "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" (emphasis added). [18] Some of the sequestration opportunities mentioned below are currently being employed, others are in small demonstration or pilot stages and may require additional technological innovation to become economically competitive. (Irrespective of their current status all rely on the same chemical, physical or biological mechanisms / processes that nature uses effectively to sequester large volumes of carbon.)

There is considerable literature on the ability of both Market Pull policies or Technology Push policies to increase the rate of innovation.[19]. While not all of these sequestration technologies/methods are available at the current time to provide significant mitigation, they could be in the near future given the proper market. In any case, the Agency has a successful history of setting regulatory "reach" targets (e.g., CAFE standards).

If information on the efficacy of sequestration technologies is inadequate to determine if the risk is unreasonable, Petitioner asks that the Agency use TSCA Section 4 to remedy the inadequacy. The Agency has in the past required TSCA test rules for many chemicals already released and in the environment in high volumes (such as dyes, plasticizers, flame retardants) to determine if treatment/mitigation methods (for example aerobic digestion) are sufficient to reduce the risk to human health and the environment to a reasonable level. Petitioner asks the Agency to assess the information available on the efficiency and cost of sequestration technology and methods to treat/mitigate released CO_2 to determine the adequacy of data for the purpose of a robust unreasonable risk determination. Petition asks that the Agency by rule require that testing be conducted to address any inadequacy.

Petitioner suggests costs for testing (and for remedies under sections 6 or 9, vide infra) be apportioned among CO_2 emission contributors according to the cumulative CO_2 emission inventory information the Agency has collected. This could be structured similar to the sponsorship format used in TSCA's High Production Volume (HPV) Program (a more complex format than for a single chemical, i.e., CO_2, it covered thousands of chemicals and thousands of tests from both foreign and domestic sources). [20]

Since any carbon emissions that result from sequestration actions must be subtracted to calculate net carbon sequestration, the Agency should in particular examine options that rely (completely or substantially) on alternative energy, such as biosequestration relying on solar power. Nature removes an order of magnitude more carbon out of the atmosphere every year using natural processes. By increasing the process area, volume, or efficiency of these naturally occurring processes gigatons of carbon can be sequestered. For example, grass pastures can build soil carbon slowly through microbial processes. Legume-based pastures that fix N and drive higher biomass

[18] TSCA section 6a (4)
[19] "Impact of Renewable Energy Policy and Use on Innovation"A Literature Review, Felix Groba and Barbara Breitschopf 2013, Deutsches Institut für Wirtschaftsforschung
[20] EPA, High Production Volume (HPV) Challenge; http://www.epa.gov/chemrtk/index.htm

production of associated grasses, drive a more rapid carbon accretion.[21] Marginal lands can be managed to trap a ton of carbon per hectare a year to equilibrium with proper management. Enhanced soil carbon is beneficial not only from it's increased productivity but also because it enables greater infiltration and retention of rainfall and this compensates for expected increases in temperature and more uncertain rainfall. In the oceans, microalgae can be fertilized sequestering carbon and then removed- harvested for products. For example the nutritional value of micro algae[22], and it's potential as a biodiesel source[23] have been extensively researched. Including ancillary benefits like these with the net sequestration benefit will provide a more complete analysis.

Recently, the World Bank investigated the capacity of different agricultural land use management practices to sequester carbon. Biomass, and especially it's soils, sequester carbon out of the atmosphere and this role as a carbon sink and as a carbon store can be strategically optimized through proven farming techniques and methods that simultaneously reduce emissions. These technical elements of climate-smart agriculture are well understood, and in addition to their technical feasibility, they can be highly productive and profitable. In the Report they estimate a enormous capacity of agriculture to sequester carbon and in turn provide marketable carbon offsets. Looking at different scenarios, that are based on different levels of international integration and ecological concern, the employment of land use and management techniques in Asia, Africa and Latin America could sequester between 12 and 18 Gt of carbon, with net positive welfare benefits, of between 1.4 and 1.6 trillion dollars by 2030. [24]

More aggressively, it has been proposed that lignin rich crops, which sequester carbon refractorially, might be used directly as a soil amendment to enrich and provide carbon to desertified or otherwise depleted lands, enabling the growth of more lignin crops to produce additional fertile soils, geometrically magnifying the sequestration.[25] Climate change may worsen desertification because of temporal changes in radiation, wind, temperature, rainfall and other parameters driven by the increased energy in the atmosphere[26]. Another economically beneficial use for tree, litter and other forestry and agricultural high lignin sources (>15%) would be for erosion control necessitated by the expected increase in rainfall in many areas from the rising temperatures.[27]

Sustainable biocharring has both an energy and a sequestration component. biocharring can be used to produce fuels and the char itself can be used to increase soil fertility and NPP, enabling sequestering more carbon. Researchers estimate that up to 12% of anthropogenic emissions can be offset by biochar. [28]

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[21] Dalal, RC, Strong, WM, Weston, EJ, Cooper, JE, Lehane, KJ, King, AJ, Chicken, CJ (1995). Australian Journal of Experimental Agriculture, **35**
[22] FAO Fisheries Technical Paper 361
[23] NREL/TP-580-24190
[24] Carbon Sequestration in Agricultural Soils, The World Bank, REPORT NO. 67395-GLB, 2012
[25]pp 150-168, Viviani, Bioenergy and Biobased Products, DOE National Bioenergy Center Strategic Partnerships Workshop April 11-12, 2001 Colorado
[26] World Meterological Oraganization, Climate_Change Desertification, 2007.
[27]Trees, Crops, and Soil Fertility: Concepts and Research Methods edited by G. Schroth, Fergus L. Sinclair
[28] Nature Communications 1: 56 doi:10.1038/ncomms1053

Reforestation and reducing deforestation can also play enormous roles and most importantly, they provide a relatively straightforward remedy that can be paid for directly by those found responsible under TSCA for the legacy carbon in the oceans. Reforestation to combat desertification is underway in Mongolia by the Mongolian government and South Korean[29]

Additionally, "blue" or coastal carbon can also play a very significant role. NOAA is encouraging the conservation of these coastal sinks and points out that current studies suggest that mangroves and coastal wetlands annually sequester carbon at a rate two to four times greater than mature tropical forests and store three to five times more carbon per equivalent area than tropical forests.[30] Most coastal blue carbon is stored in the soil, not in above-ground plant materials (biomass), as is the case with tropical forests.

The Agency should also examine options which produce (and net) carbonates from carbon dioxide[31], especially those producing salable products, such as carbon mineralization processes making carbonate building materials from carbon dioxide, e.g., green bricks and green cement, and can net energy. Building materials comprise an enormous market, as there are about 30 billion tons of concrete produced and used each year alone. Concrete accounts for about 7% of global carbon emissions. Sequestering CO_2 into green cement provides multiple opportunities and benefits: potential increases in concrete's strength, reductions in emissions, carbon sequestration, and provides significant opportunities for offset purchase.

The use of timber in high rises (to 40 stories or some cases more) to replace some of the concrete and steel can also reduce the carbon footprint of construction drastically (as both concrete and steel are carbon intensive) and can sequester atmospheric carbon at the same time. A cubic meter of wood substituted for other construction material can result in savings of 0.75 to 1 ton of CO_2.[32] This can reduce the carbon footprint of buildings by two thirds.

Practice and performance based economic incentives could be used to encourage sequestration in the building and forestry/agricultural sectors. Banked credits could be sold to offset any added cost from the differing practices/products. In the US, government construction accounts for about a quarter of new projects. These projects could account for significant sequestration if additional green construction were required to be incorporated in design. In government directed economies it could be higher.

3D printers, which can and do use biological materials (containing carbon harvested from the atmosphere) as substrates can produce myriad consumer products. This is particularly helpful because increased consumer expenditures and economic growth is almost always associated with increased energy/resource use and drive carbon emissions. In this case consumer purchases can

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[29] Min-Kyung Kang et al, Jour. Korean For. Soc. Vol. 99 No. 5, pp 655-663 (2010)
[30] http://www.habitat.noaa.gov/coastalbluecarbon.html
[31] Annu Rev Chem Biomol Eng. 2013;4:103-17. doi: 10.1146/annurev-chembioeng-062011-080951. Epub 2013 Feb 28.
[32] International Institute for Environment and Development, Using Wood Products to Mitigate Climate Change, 2004

actually reduce net atmospheric carbon. Other research demonstrates direct storage of CO2 into nonbiological compounds which can also be accessed to make consumer products[33]

These sort of options help bring the economic carbon cycle more into balance, providing value by removing carbon from the atmosphere. CO_2 not only becomes an essentially limitless resource, which can be both reduced or oxidized to produce products and/or energy, it also couples sequestration with population and economic growth.

The Agency, through TSCA section 9's access to other Federal programs, could use economic incentives to foster growth of some these options by the general population. For example, DOE and EPA's Energy Star program has prevented 1.8 billion tons of GHG emissions, by providing information that helps consumers select energy efficient devices. A similar program could be established that provides information about the net amount of atmospheric carbon sequestered in products.

Providing information to consumers concerned about ocean acidification (and climate change) enables them take direct action to mitigate these problems, and also provides a marketing incentive to companies to develop and sell these products. There is already a trend in the US for development of biocarbon products substituting for petroleum or mineral based products. Examples range from large volume products, such as home foam insulation based on soy, to smaller niche products, such as wetsuits made using biorubber rather than petroleum based neoprene (Patagonia).

As mentioned above, Nature cycles atmospheric carbon primarily by storing it in the ocean, reducing it into biological materials and oxidizing it into minerals. This latter process also provides sequestration opportunities. The IPCC [34]estimates that magnesium and calcium silicate deposits are sufficient to fix all the CO_2 that could be produced from the production of all fossil fuels resources. There have been demonstration and pilot projects that have sequestered carbon at a costs ranging from $50 to $300/ ton.[35] Some of these processes also have the advantages of yielding salable product. For example olivine has been used as an amendment to replenishing beach sand, and the weathering of the sand from the ocean waves has the potential to raise the pH of the waters.[36]

There are high volume industrial waste materials, such as 'red mud' from aluminum production[37] as well as steel and blast furnace slag, fly ash and waste concrete that can sequester atmospheric carbon, and in some cases produce salable products[38]

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[33] CO_2 Coordination by Inorganic Polyoxoanion in Water, Guanggang Gao et al, JACS communications, 2008

[34]IPCC Special Report Carbon Dioxide Capture and Storage, 2005

[35]Chem. Soc. Rev., 2014, 43, 8049

[36]International Journal of Greenhouse Gas Control 4 (2010) 855–856

[37]Peterson et al. Science of The Total Environment Volume 338, Issue 3, 15 February 2005

[38] Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard USEPA, February 2014

IntraAgency Coordination

Petitioner is aware that the Agency has operated cross-Agency programs, i.e., initiatives that all media program and other offices are required to participate in. Examples include, P2 Pollution Prevention, the IntraAgency Integration Program and the Priority Pollutant Program, all of which required coordination to achieve an environmental goal(s). Almost every Agency action, initiative, grant, etc. has carbon implications. Petitioner asserts that Ocean Acidification is, at the very least, on a par with the problem these programs were designed to address. If this is not already being done, the petitioner asks the Agency to require that all significant actions take carbon benefits explicitly into account.

The Economic Costs of CO_2 and Discount Rate

The discount rate is critical in the unreasonable risk determination, as benefit estimates depend heavily on the discount rate applied. There is debate as to applicability of current methodologies to derive these rates when applied to distant events and transgenerational effects. As Cowen and Parfit pointed out "Why should costs and benefits receive less weight, simply because they are further in the future? When the future comes, these benefits and costs will be no less real. Imagine finding out that you, having just reached your twenty-first birthday, must soon die of cancer because one evening Cleopatra wanted an extra helping of dessert".[39]. Or putting it in terms of dollars instead of baklava: Frank Partnoy, (University of San Diego) observed "A human life is often estimated to be worth around $10 million. But if you apply a three percent discount rate to this, that means that a human life five hundred years from now is only worth $3.81 today."

Further, the basis for a discount rate is the opportunity cost of taking action today to avoid future effects, i.e., the discount used must reflect the profitability of the best alternative investment opportunity. However, global warming, and even ocean acidification will have such enormous effects on agriculture, real estate, water availability, fisheries, etc, that investments in many sectors could well have limited or even negative discount rates without mitigation action. People may well be poorer in the future because of ocean acidification and climate change and have less rather than more resources to mitigate and adapt[40].

To use an ocean acidification example, an investment in ocean property in Florida could well have a negative return (if not for the owner, than for federal government which guarantees flood insurance) when the coral reefs erode and flatten (as discussed in the body of the petition) and fail to provide adequate buffer for storm surges, as could investments in commercial fisheries. Climate change effects on investment returns would be even larger. For example, the IPCC predicts a 2% net decrease in agricultural production per decade from global warming. Petitioner asks the Agency to take into account how ocean acidification and climate change will affect return on capital investment when setting a discount rate in their assessment of benefits as recommended in USEPA's Guidelines for Preparing Economic Analysis. OMB Guidance on regulatory analysis states " In some instances, if there is reason to expect that the regulation will cause resources to be reallocated away from private investment in the corporate sector, then the oppor-

[39]Tyler Cowen and Derek Parfit, Against the Social Discount Rate, in Peter Laslett and James S. Fishkin, eds, Justice Between Age Groups and Generations 144, 145 (Yale 1992).
[40] Johnson et al, Journal of Environmental Studies and Sciences September 2012, Volume 2, Issue 3, pp 205-221

tunity cost may lie outside the range of 3 to 7 percent. ” [41] The same logic must apply when it is not the regulation but the effect itself that provides an economic distortion in the absence of regulation.

Petitioner asks the Agency to consider and explain the choice of using either a Willingness to Pay (WTP), or a Willingness to Accept (WTA) in the economic valuation of benefits. This seems germane relative to the loss of oceanic buffering capacity due to past absorption by the 600 billion tons of carbon emissions from the burning of fossil fuels. Like many other effects of Ocean Acidification this loss of capacity is not presently included in the calculation of the SCC. If the Agency decides to use a Contingent Valuation Method to value the lost buffering capacity, then WTA may be appropriate as this capacity is a public good. [42]

Low Probability Catastrophic Impact Effects

Current climate cost and benefit estimates do not take into account many low probability effects with catastrophic impacts. For example, there is research to estimate probability densities for positive feedback and/or climactic tipping points, such as unstable methane deposit releases from permafrost[43], the collapse of the marine food web, impacts to cloud albedo[44], or alterations in ocean circulation[45]. These may be low probability events, but have enormous consequences. Many of these can have catastrophic Earth System effects and once they occur are essentially irreversible. Because of this, current cost and benefit estimates must be considered conservative.[46]

This is one of the reasons why the President’s Council of Economic Advisors recommended treating Climate Change prevention action as an insurance investment. Current regulations, proposed regulations, and planned regulations, do not address these severe Earth System potential impacts and do not, measurably decrease their likelihood of occurrence. Petitioner agrees with the President’s Council that Climate Change be treated as an insurance investment, and asks that the potential cost of these low probability, very high impact effects, be valued to inform the TSCA section 6 unreasonable risk decision. In lieu of a better Agency alternative, Petitioner suggests the Agency estimate the cost of an insurance premium using occurrence and impact probability of these tipping points/catastrophic events as basis, much like insurance premiums in

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[41] OMB Circular A-4

[42]Kahneman et al, Journal of Environmental Economics and Management, 22 57-70, 1992

[43]Schaefer, K., T. Zhang, L. Bruhwiler, and A. P. Barrett (2011), Amount and timing of permafrost carbon release in response to climate warming, Tellus Series B: Chem. Phys. Met., DOI: 10.1111/j.1600-0889.2011.00527.x.; oven teal, Analysis of Permafrost Thermal Dynamics and Response to Climate Change in the CMIP5 Earth System Models, JOURNAL OF CLIMATE
2013

[44] Six K.D., Kloster S., Ilyina T., Archer S.D., Zhang.K, Maier-Reimer,E., Global warming amplified by reduced sulphur fluxes as a result of ocean acidification. Nature Climate Change, doi:10.1038/nclimate1981, 2013.

[45] Rahmstorf, S., Box, J., Feulner, G., Mann, M., Robinson, A., Rutherford, S., Schaffernicht, E. (2015): Evidence for an exceptional 20th-Century slowdown in Atlantic Ocean overturning. Nature Climate Change (online) [DOI: 10.1038/nclimate2554]

[46]Weitzman, Martin L. 2009. Review of Economics and Statistics 91(1): 1-19.

the nuclear energy industry against catastrophic incidents are calculated and apply that as a surrogate for the cost of not reducing carbon emissions to mitigate ocean acidification and accompanying climate benefit.

Other Insurance Considerations

Petitioner asks that the Agency consider as a cost any direct insurance impact from Climate change: "Climate change can also adversely impact the prevalence of vector-borne diseases, food poisoning, water quality, aeroallergens, and the health of natural systems that can cause economic losses for humans, sometimes insured" "Changing weather patterns and rising ocean temperatures as a result of climate change will also likely continue to put financial stress on the National Flood Insurance Program (NFIP). Currently, the NFIP has a $19 billion deficit, and this deficit may increase each year because of $900 million in subsidies to properties that are not paying actuarially based rates. In addition, the cost to the NFIP of servicing its debt consumes much of its revenue. ... millions of Americans depend upon the NFIP for flood coverage ..."

According to Dr Evan Mills (US Department of Energy's Lawrence Berkeley National Laboratory) "there is growing acknowledgement among insurers that the impact of climate change on future insured losses is likely to be profound. The chairman of Lloyd's of London has said that climate change is the number- one issue for that massive insurance group. And Europe's largest insurer, Allianz, stated that climate change stands to increase insured losses from extreme events in an average year by 37 per cent within just a decade. Losses in a bad year could top US$1 trillion. Insurers increasingly recognise that it is the lack of action to combat climate change that is the true threat to their industry and the broader economy; engaging with the problem and mounting solutions represents not only a duty to shareholders but also a boon for economic growth.

The insurance sector thus finds itself on the front lines of climate change. The response of many, particularly in the United States, has been to focus on financial means for limiting their exposure to high-risk areas along the coastlines and areas prone to wildfires. Allstate, for instance, has said that climate change has prompted it to cancel or not renew policies in many Gulf Coast states, with recent hurricanes wiping out all of the profits it had garnered in 75 years of selling homeowners insurance. [47]The company has cut the number of homeowners' policies in Florida from 1.2 million to 400,000 with an ultimate target of no more than 100,000. The company has curtailed activity in nearly a dozen other States."

EPA Can Use TSCA to Complement Existing Federal Laws

Petitioner asks that, as required under TSCA, the Agency determine if relief is more efficient under any other Federal statute and if so, to use that authority as is required under TSCA § 9. Choosing a regulatory strategy and determining what actions are required to mitigate unreasonable risks is, again, inherently a governmental function. However, the cost and the efficiency of the mitigation options that are considered during regulatory development and assessment drive the determination of whether a risk is "unreasonable" and the array of alternatives considered need to be robust.

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[47] Conley 2007 in "Insurance in a Climate of Change: Availability & Affordability." Berkeley Lab, U.S. Department of Energy.

Because of the magnitude of Ocean Acidification risk, Petitioner believes good government demands the Agency consider a complete array of options using all authorities and tools available to efficiently address the problem. Petitioner will show that in addition to requiring relief under TSCA § 6, the Agency can use the TSCA § 9 authority to require action under either, or both, the Clean Air Act (CAA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) authorities. Relief under these statutes should also be considered in determining the cost, benefit and the most efficient remedies to mitigate the harm and risk from Ocean Acidification.

Petitioner is aware that the Agency has recently planned and initiated several emission reduction actions aimed at slowing the rate at which carbon emissions are increasing. These actions by themselves while laudable, will not stabilize atmospheric CO_2 at a level that prevents widespread harm from ocean acidification. Consider that even with a successful implementation of the Agency's planned emission reduction regulations, atmospheric concentration will pass 450 ppm around 2030, a tipping point likely to induce aragonite undersaturation in surface waters. Petitioner believes that a combination of aggressive emission reduction and sequestration is necessary to mitigate the unreasonable risk and harm caused by ocean acidification. Both CERCLA and the CAA can provide relief.

Petitioner asks that the Agency consider whether that CERCLA and/or CAA authorities present efficient opportunities for remediating ocean acidification.

1) **Remedies under the Clean Air Act (CAA)**

There are several remedies under the CAA either directly accessible or accessible under TSCA section 9. Title 42 § 7415 of the Clean Air Act addresses endangerment of public health or welfare in foreign countries from pollution emitted in United States, and directs "the Administrator, upon receipt of reports, surveys or studies from any duly constituted international agency"...to have... " reason to believe that any air pollutant or pollutants emitted in the United States cause or contribute to air pollution which may reasonably be anticipated to endanger public health or welfare in a foreign country ...the Administrator shall give formal notification thereof to the Governor of the State in which such emissions originate. The notice of the Administrator shall be deemed to be a finding under section 7410 (a)(2)(H)(ii) of this title "

There have been many reports addressing the endangerment of public health or welfare from ocean acidification that have been published by duly constituted international agencies and of which the Agency is well aware and in some cases participated in. These include: the Royal Society[48]; The European Union's European Project on Ocean Acidification (EPOCA) published over a hundred scientific papers detailing the effects; the UN's Climate Change and Ocean Acidfication Synegies and opportunities within the UNFCCC, Harrould-Kolieb and Herr; and Australia's GBRMPA published Climate Change and the Great Barrier Reef: A Vulnerability Assessment in association with 85 scientific and management experts; as well as numerous IPCC Reports, in which the Agency and other Departments of the Federal Government actively participate.

[48]Royal Society (Ocean acidification due to increasing atmospheric carbon dioxide, 30 June 2005

The Columbia Journal of Law[49] describes the applicability of Section 115 to CO_2 regulation for ocean acidification mitigation, including the legislative history and how SIPs under section 7410 are mandated. The Agency's current Proposed Rule for Electric Utilities using section 7411, can serve as a template. The flexibility for State SIPs in the Rule includes by reference, their current State programs as applicable to compliance with the Rule. Some of these cited include provisions for, and allow "offsets" or carbon sequestration to be counted in reaching program goals, using for example, Cap and Trade. State by State assessment of legacy carbon could be calculated by the Agency from the Emission Inventory and these could be included in State Implementation Plans.

§ 7415 includes the requirement that a reciprocity finding that the affected foreign country gives the U.S. "essentially the same rights with respect to the prevention or control of air pollution occurring in that country as is given that country". This requirement directly addresses the often raised argument against US EPA action that posits: since Ocean Acidification has a global cause, only international action can address it successfully. Implementation of State plans would presuppose a concurrent implementation internationally. The Montreal Protocol (which found it's genesis in a TSCA action) could serve as a template for coordinating international plans for ocean acidification mitigation. The European Union's REACH (Registration, Evaluation, Authorization and Restrictions of Chemicals) regulation serves as an example of how a large attractive market (like the EU or the US) can induce foreign companies and government directed economies who wish to have continued access to the markets, to comply with environmental regulation.

Recently the US and China, which account for almost 40% of global carbon emissions, jointly announced new targets to cut emissions. Germany, Finland and other industrialized counties are also drastically cutting emissions. The foundation for a reciprocity agreement with the nations that account for most of the legacy and current emissions is already in place.

Alternatively, the CAA emission trading mechanism, which offers an often used, efficient market approach might also be accessed directly through TSCA section 9 to mitigate ocean acidification.

Under TSCA section 6: (1) A requirement ...." (B) limiting the amount of such substance or mixture which may be manufactured, processed, or distributed in commerce." ...clearly gives the Agency authority to limit current emissions, and Section 6's: "Any manufacturer or processor subject to a requirement to replace or repurchase a chemical substance or mixture may elect either to replace or repurchase the substance or mixture and shall take either such action in the manner prescribed by the Administrator." gives authority for trading options. While 'repurchase' is sequestration, "replace" is trading.

Since EPA has treated air pollutants like CO_2 as fungible in order to efficiently regulate when the "net" pollution is key, replacing carbon emitting facilities with new facilities that rely on renewable sources will reduce the net carbon in the atmosphere and thereby reduce the amount in the oceans. This would be one way for facilities to "pay down" their legacy carbon debt. The

[49]Cap-and-Trade Under The Clean Air Act?: Rethinking Section 115 , H Chang, April 2010

Agency could consider a current carbon emitting facility's development of green (e.g. solar or wind) energy capacity to *replace* (not augment) fossil energy as a legacy offset. (Assuming this is not double counting, i.e., being used to bring the facility into compliance for current emissions under another requirement). The new energy production from the no- or low- emitting source would "replace" the carbon that would be emitted from the existing energy production source, leading to a net reduction in carbon emissions. This type of offset also has the advantage of helping to build the market base for green energy and eventually lower costs for additional facilities, accelerating the needed energy infrastructure change. This is an approach the German State is pursuing through subsidies.

2) Remedies under CERCLA Under the 42 U.S. Code § 9604 Response authorities

Whenever (A) any hazardous substance is released or there is a substantial threat of such a release into the environment, or (B) there is a release or substantial threat of release into the environment of any pollutant or contaminant which may present an imminent and substantial danger to the public health or welfare, the President is authorized to act (under 42 U.S. Code § 9621), consistent with the national contingency plan, to remove or arrange for the removal of, and provide for remedial action relating to such hazardous substance, pollutant, or contaminant at any time (including its removal from any contaminated natural resource).

CO_2 can meet the CERCLA definition of "hazardous substance in in either of two ways: 1) under 9602 "The Administrator shall promulgate and revise as may be appropriate, regulations designating as hazardous substances... such elements, compounds, mixtures, solutions, and substances which, when released into the environment may present substantial danger to the public health or welfare or the environment, or, 2) by definition: "any imminently hazardous chemical substance or mixture with respect to which the Administrator has taken action pursuant to section 7 of the Toxic Substances Control Act".

If the Administrator takes action under TSCA §7 based on the imminent hazard to coral reefs and marine life, as explained in the petition, CERCLA becomes applicable[50]. While some risks to marine organisms from ocean acidification may be uncertain, many are not. Also, the risk to the coral reefs which provide protection to life and property along America's coastlines as well as significant recreational and nutritional benefits is both manifest and well documented and the risk is "imminent" within the definition of TSCA. (Alternatively, these same dangers might be used by the Administrator to directly designate CO_2 as a hazardous substance)

The imminence stems not from the point in time when the threat will be completely manifest but rather from the point in time when action must be begun to effectively mitigate or avoid the threatened effect(s). That time is now, primarily because of the enormous inertia in the carbon economic cycle. The infrastructure of energy use relies on fossil fuel combustion. There are no alternatives of sufficient capacity in the near term. To avoid reaching the point, mid to late century (given the current trajectory) where the oceans are undersaturated in carbonate and shells and coral begin dissolving wholesale, either a robust sequestration program must be developed,

[50] CERCLA section 101(14)

and/or significant energy alternatives must be made available. These are both long term programs that require decades, and must begin now.

Scientists are well **aware of the enormous risk posed by ocean acidification.** A recent study in Science found that the largest extinction event on earth was caused by ocean acidification[51]. **Dr. Jane Lubchenco, The head of the National Oceanic and Atmospheric Administration from 2008 -2013 has called ocean acidification global warming's "equally evil twin."** Unfortunately, unlike the risk from Climate Change, the magnitude of the risk to the oceans from acidification is not well known or understood by the general public. A TSCA § 7 Notice informing the public of the serious risks to coral reefs, provides the information needed to decide if changes in personal energy use, and consumption is warranted. (TSCA § 7 grants EPA authority to "require warning labels and/or instructions on containers or products". USEPA could encourage consumer choice by labeling products with large embedded carbon volume).

Changes in energy use and consumption can begin to retard the ongoing increase in atmospheric CO_2 and to lessen the effect of acidification on coral reefs. Changes in consumer choice toward less carbon intensive products could build markets for those products, making them less expensive and spurring innovation. Information on the risks can help localities plan as well. Notification of risks is one of the TSCA § 7 remedies. A TSCA § 7 Notice explaining the risks would help inform decisions concerning where to live in order to be secure in life and property, given the inevitable loss of protection to some coastal areas from extreme weather events (coincidently expected to increase with climate change) which will occur with the loss of reefs.

It also seems reasonable that, to the extent the US is harmed, it can use CERCLA to fund remedies from transboundary actors, as was the case in the Trail Smelter Arbitration.[52] Wherein the downstream Confederated Tribes of the Colville Reservation, and the State of Washington, in the US sued a Canadian smelter for dumping into the Columbia River upstream in Canada under CERCLA. This is a successful resolution of an international dispute that provided an important principle of international customary law concerning state responsibility and transboundary pollution. (Again, a TSCA § 7 action for CO_2 effect on coral reefs would define CO_2 as hazardous under CERCLA.)

Another important theory of international law is the polluter-pays principle. This theory stands for the proposition that nations should focus on internalizing environmental costs for purposes of public interest by making the polluter bear the cost of pollution. By mandating that the responsible party bear these costs, the polluter-pays principle achieves the effect of encouraging individual responsibility for environmental harm. The countries attending the Rio Convention, including the US and Canada, reaffirmed this principle in Article 16 of the 1992 Rio Declaration"[53] CERCLA's strict, joint and several liability, holds polluters responsible for damage.

The oceans have essentially been a "dump site" for CO_2 emissions, so CERCLA is a natural vehicle for seeking remedy. CERCLA has been applied to other water bodies, e.g., the upper 40 or

[51] Clarkson et al. Science 10 April 2015: Vol. 348 no. 6231 pp. 229-232
[52] United States District Court for the Eastern District of Washington, April 4, 2012
[53] Greenfield: CERCLA'S applicability abroad, Emory International Law Review;Fall2005, Vol. 19 Issue 3, p1697

so miles of the Hudson are a NPL site for pcb contamination. CERCLA is an excellent tool for seeking remedy from multiple, diverse parties, i.e., "CERCLA casts a wide net in bringing in responsible parties. Through the broad definition of hazardous substance (§101(14) - liability is extended to anything that presents an "imminent and substantial danger"), the loose interpretation of "release" (there is no time constraint on this) and the wide scope of liability (each party involved may be responsible for the entire clean up) the statute seeks to fund the clean up of these sites. Although there have been challenges to the apparently retroactive nature of this (because people are being held liable for actions that predate the statute), and as noted above, the courts have held that as the waste is continuing to cause problems, and the statute is not a punishment but rather a reimbursement obligation, the statute is not retroactive, and thus not unconstitutional. And again, small contributors can be and are routinely ignored if transaction costs are high.

Summary

Ocean acidification and its effects are complex and the state of knowledge is uneven. Depending on what USEPA knows and believes about the effects of ocean acidification there are a number of decisions that the Agency must make and actions associated with those decisions. In the introduction and in the body of the petition, petitioners ask USEPA to take several actions under TSCA § 4 and 6, and in this supplement petitioner asks the Agency to take additional appropriate actions under other federal statutes through TSCA § 9 and other TSCA authority, in order to mitigate the human health and environmental risk from ocean acidification caused by CO2 emissions.

The following describes the different paths the Agency can take in responding and what the petitioner believes the public deserves in each case. While mentioned below is the possibility of taking action under TSCA § 7, petitioner understands that § 21 cannot be used to for § 7 action, however, petitioner believes that the threat to coral reefs presented in the petition and as discussed herein make a compelling case for § 7 action.

1) EPA could decide that the current state of knowledge concerning ocean acidification is sufficient to decide that the risk(s) of ocean acidification are not unreasonable. This requires evidence that the demonstrated loss of the coral reefs, decrease in shell fish harvests, loss of competitiveness of pteropods and other organisms that secrete calcium carbonate and other ecological and health effects are known to the Agency, as are the ancillary climate benefits that occur with atmospheric carbon controls, are either outweighed by the cost of mitigation, which is also known to the Agency, or are not significant effects. In this case, petitioner asks that the Agency publish and share this information with the public.

2) EPA could decide that all or some of the information necessary to make the unreasonable risk finding is either not sufficient or not available, but this lack of data does not meet the criteria for action under TSCA § 2(b)(1) and/or TSCA § 4 . Petitioner expects in this case, an explanation of why the triggers are not met by the information presented in the petition. Since much of the risk cited in this petition come from EPA, NOAA, and other government sources, petitioner asks if USEPA has information that supersedes or discounts these conclusions, and if so to publish and share this information with the public.

3) EPA could decide that all or some of the information necessary to make the unreasonable risk finding is either not sufficient or not available, and take action under TSCA § 4. Petitioner expects in this case that the Agency will explain what information is sufficient and what is not, and develop test rules to gather information sufficient to make an unreasonable risk finding in a timely fashion.

4) EPA could decide that some of the risks from ocean acidification are unreasonable and take action under TSCA §'s 6, 9 and other statutes, but that some information is lacking for other risks and write a TSCA § 4 rule to develop the missing information. Petitioner expects in this case that the Agency will explain what information is sufficient and what is not, develop test rules to gather information sufficient to make an unreasonable risk finding for the risks that are uncertain, and take action for the risks that are unreasonable.

5) The Agency, in combination with any of the above options, could publish a TSCA § 7 Notice informing the public of the serious risks to coral reefs associated with ocean acidification, it's causes, and what must be done to mitigate it. As explained above this information is needed by the public to judge the severity of the risk, adequacy of governments response to protect human health and the environment, and what precautions, if any, are necessary to take.

6) EPA could grant the petition and propose rules to mitigate ocean acidification using TSCA, CERCLA, CAA and/or other Agency and Federal authorities as appropriate. Petitioner endorses this action.

Sincerely,

/s/ Donn J. Viviani

Donn J. Viviani PhD.

Donn J. Viviani 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 Quality 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 greatly enjoys the ocean and cosigns the petition and submits this supplement, in part, so his grandchildren will be able to enjoy it as well.