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September 27, 2007 CDM Project File: 5000-55353

Ms. Ana Townsend
California Regional Water Quality Control Board - Los Angeles Region
320 W. 4th Street, Suite 200
Los Angeles, California 90013

Subject: Pre-Remediation Activities Documentation Report
Boeing Realty Corporation, Former C-6 Facility
19503 South Normandie Avenue
Los Angeles, California (Site)
SLIC # 410

Dear Ms. Townsend:

On behalf of Boeing Realty Corporation (BRC), Camp Dresser & McKee Inc. (CDM) is submitting this Pre-Remediation Activities Documentation Report (Report) documenting the activities conducted to date and the status of the remaining activities associated with the Pre-Remediation Work Plan (Work Plan) (CDM, February 14, 2006) approved by the California Regional Water Quality Control Board - Los Angeles Region (LARWQCB) on February 23, 2006 for the above-referenced Site.

Since the submittal of the Work Plan, BRC has reevaluated and changed the overall remediation approach at the Site. An Addendum to Building 1/36 (Parcel C) Source-Area Groundwater In-Situ Reactive Zone Pilot Study Workplan (Workplan Addendum, CDM, February 1, 2007) was submitted to and approved by the LARWQCB (letter dated April 3, 2007) to implement a pilot biorecirculation study at the Building 1/36 area. The proposed pilot study consisted of semi-continuous amendment injections at low operating pressures and bioaugmentation to promote the complete biodegradation of contaminants. The pilot study was initiated in September 2007 under an individual Waste Discharge Requirements (WDR) Permit issued for the Site by the LARWQCB (August 10, 2007). As indicated in the Workplan Addendum and the LARWQCB April 3, 2007 approval letter, this Report is being submitted in lieu of the Remedial Action Plan (RAP) which was originally planned to be submitted following the completion of pre-remediation activities as outlined in the Work Plan.

As a result of the change in the remedial approach approved by the LARWQCB, some of the pre-remediation activities have been completed while others have been either delayed or eliminated.

The pre-remediation activities completed to date include:

- Existing remediation infrastructure evaluation using existing data;
- Installation of new groundwater wells; and
- Electron donor evaluation and treatability study.

The pre-remediation activities that have been either delayed or eliminated include:

- Hydraulic testing of existing remediation infrastructure;
- Aquifer performance testing;
- Groundwater modeling; and
- Electron donor injection testing.

These are discussed in the following sections.

1.0 Completed Activities

1.1 Existing Remediation Infrastructure Evaluation

CDM performed a detailed evaluation of the existing remediation infrastructure at the Site to determine its usability for certain remediation techniques such as biorecirculation. To this end, we reviewed pre-existing documents and data, including pre-injection test and well installation and development data.

Former Building 2

The acceptability assessment of the 169 amendment wells in Former Building 2 area was based on flow rates, injection volumes, injection pressures, and field personnel observations during injection. These field observations included:

- observations of surface leakage;
- observations of siphoning during injection and after flow ceased;

- observed halts in flow during injection testing; and
- changes in performance after bleeding wellhead pressure.

This evaluation of the 169 wells indicated that 17 wells are acceptable for use without further testing, 18 wells are not acceptable because of previous surface leakage, and 134 wells will require additional field hydraulic testing prior to use, as discussed in Section 2.1.

Former Building 1/36

The acceptability assessment of the 163 amendment wells installed in the Former Building 1/36 area were based primarily on the results of prior brief water injection testing activities and a review of the well installation and development data. The criteria for evaluation consisted of the following:

- Whether the well had received any water injection testing;
- Ability to sustain measurable flows;
- Water levels during injection ; and
- Water level recovery rates after injection ceased.

This evaluation indicated that 131 of the 163 wells are acceptable for use without further testing. Of the remaining 32 wells, 14 wells have had no testing done, while 18 wells had a combination of poor recovery, higher than anticipated water level rise during testing, and inability to sustain more than 5 gallons per minute (gpm). These remaining 32 wells may require additional field hydraulic testing prior to use, as discussed in Section 2.1.

1.2 Groundwater Well Installation

The Work Plan called for the installation of two extraction wells to facilitate aquifer testing in locations that are potentially suitable for incorporation into the remedial design. A total of six wells (five C-Sand wells and one B-Sand well) were installed in October and November 2006. Two wells (one B-Sand and one C-sand) were installed in the northern parcel (Former Building 1/36) instead of the one well (B-Sand only) originally proposed in the Work Plan. A total of four C-Sand wells were installed in the southern parcel (Former Building 2). Appendix A contains a well completion report documenting the field installation procedures along with the well construction logs for all the wells.

As documented in our letter to LARWQCB (Notifications of Deviations to Pre-Remediation Work Plan, CDM, October 12, 2006), CDM anticipates that these changes would serve to facilitate the future implementation of groundwater remediation. Based on the change in

remedial approach, the B-Sand well EWB001 is currently being used as an extraction well for the pilot biorecirculation test at Former Building 1/36, while the rest of the wells are being used as routine monitoring wells.

1.3 Electron Donor Evaluation and Treatability Study

CDM conducted an electron donor evaluation to identify the most suitable electron donor compound(s) for use in the remediation of volatile organic compound (VOC)-impacted groundwater at the Site. In order to appropriately consider the factors that affect electron donor selection, the evaluation was conducted in two phases: a background "paper" evaluation; and a laboratory treatability study.

1.3.1 Electron Donor Evaluation (Paper Study)

A preliminary "paper" evaluation was conducted in order to determine which donors would be suitable for additional testing. Appendix B contains a report documenting the results of the paper evaluation and providing recommendations for donors to be further evaluated in the electron donor laboratory treatability study. The "paper" evaluation provided the following recommendations:

- Perform laboratory treatability study to further evaluate the following electron donors: Citrate; Whey powder; Lactate; JRW proprietary fermentation mother liquor; Whey powder plus JRW nutrient; and Newman Zone.

- Each of these donors should be tested with no bioaugmentation culture, with a culture from SiRem, and with a culture from Shaw. In addition, the microcosm should be spiked with 1,1,1-trichloroethane (1,1,1-TCA) and chloroform as appropriate to allow an assessment of the degradative capabilities of the cultures toward these compounds, as well as the extent to which these compounds inhibit chloroethene degradation. The spike concentrations to be selected would be representative of the site groundwater based on the most recent groundwater sampling data available at the time of the laboratory study (March 2006).

1.3.2 Electron Donor Laboratory Treatability Study

A laboratory treatability study was conducted to evaluate six electron donors (selected based on the Paper Study) and two bioaugmentation cultures for potential use at the Site. Appendix C contains a document which describes the treatability testing methodologies; summarizes the results of the laboratory treatability study with detailed charts and tables; and provides conclusions and recommendations for electron donor use and bioaugmentation at the Site. Key recommendations from the treatability study are summarized below:

- Based on the lab study results and the economic analysis presented in the Technical Memorandum, whey was the preferred donor for the pilot study, with lactate as a backup should logistical issues (i.e. mixing, storage, handling, etc) or technical performance issues (e.g., solids plugging of injection wells) be encountered with whey.

- Newman Zone was recommended for slug injections, if planned at the Site. Methane production should be taken into account and at the minimum monitored in the field when using Newman Zone.

- Shaw SDC-9™ culture is the recommended choice for bioaugmentation.

Based on subsequent evaluations, lactate was selected over Newman Zone as the donor of choice for slug injections at the Site. This was based on minimizing potential formation plugging issues that could be associated with Newman Zone in similar lithologies, the longer than expected half-life of lactate based on the previous injections at Former Building 2, and the results of the treatability study.

2.0 Delayed or Eliminated Activities

The status of the activities under this task along with the rationale for the changes is described in the following sections.

2.1 Hydraulic testing of existing remediation infrastructure

It is recommended to defer the field hydraulic testing of the existing 32 amendment wells at Former Building 1/36 pending the completion of the ongoing pilot study for the following reasons:

- The ongoing biorecirculation pilot study at Former Building 1/36 will provide us with some data on biofouling and other potential well problems that could be anticipated with a full-scale system.

- Based on the ultimate remedy for the Site, we may not need some or all of the 32 wells.

Hydraulic testing of the existing infrastructure at Former Building 2 is still recommended <u>but only</u> for certain remediation techniques such as biorecirculation. Hydraulic testing is not required prior to its use for other remediation techniques such as slug injections.

2.2 Aquifer Performance Testing

Aquifer performance testing is not recommended for Former Building 1/36 at this point, because hydraulic data obtained during the ongoing pilot study along with the historical slug

test and aquifer performance test data is expected to provide adequate information on the groundwater hydraulics.

Given the change in the remedial approach at the Site, no remediation activities are currently planned for the Former Building 2 area that would require aquifer test data. As a result aquifer performance testing activities at the Former Building 2 area are being delayed indefinitely.

2.3 Groundwater Modeling

Given the change in the remedial approach at the Site, a preliminary groundwater model was sufficient for designing the pilot study at Former Building 1/36. As with aquifer performance testing, groundwater modeling activities for the Former Building 2 area are being delayed indefinitely.

2.4 Electron Donor Injection Testing

The biorecirculation pilot study at Former Building 1/36 is expected to provide data that would have been provided by electron donor injection testing. Therefore, electron donor injection testing as proposed in the Work Plan is being eliminated.

If you have any questions or concerns regarding this report, please call the undersigned at (949) 752-5452 or Joe Weidmann at (805) 563-8600.

Very truly yours,

Ravi Subramanian

Ravi Subramanian, P.E
Principal

Attachments

Cc: Robert Scott, BRC
Mario Stavale, BRC
Joe Weidmann, Haley & Aldrich, Inc.

Appendix B

ELECTRON DONOR EVALUATION (PAPER STUDY)

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Appendix B

Electron Donor Evaluation (Paper Study) Remediation of Volatile Organic Compounds Former C-6 Facility, Los Angeles, California

An evaluation of electron donors was performed by Camp Dresser & McKee Inc (CDM) for the former C-6 Facility (Site) in order to identify the most suitable electron donor compound(s) for use in the proposed bioremediation remedy at the site. In order to consider the factors that affect electron donor selection appropriately, the evaluation was conducted in two phases – a background "paper" evaluation and a laboratory treatability study. This document presents the results of the paper evaluation and provides recommendations for donors which were further evaluated in the electron donor laboratory treatability study phase of the evaluation.

1.0 Electron Donor Background

A number of organic substrates have been used to stimulate biological reduction at various sites across the U.S. In general, electron donors can be divided into two categories – aqueous (fast release) and slow release.

1.1 Aqueous Electron Donors

Aqueous electron donors generally have high solubility and low viscosity, and are easily distributed in the subsurface. This implies that fewer injection locations can be used to deliver donor to a given area. As aqueous electron donors can facilitate the rapid onset of strongly reducing conditions to quickly poise the subsurface for efficient dechlorination, they can be considered "fast release". These donors are rapidly fermented to molecular hydrogen, which drives the dechlorination process. In addition, they generally have low unit costs (i.e. per pound or per gallon) compared to slow release electron donors. Also, some aqueous donors can cause significant enhanced dissolution from residual sources via a cosolvency effect when injected directly into a source area (Macbeth et al, 2006; ITRC, 2005; French et al. 2003; Song et al. 2002; Sorenson 2002). That is, certain aqueous donors can cause contaminants to be released from the non-aqueous phase source (DNAPL or sorbed phase) faster than under ambient conditions. This can result in more rapid degradation of a source term as contaminant mass is driven into the aqueous phase and then degraded.

However, as the term implies, fast release electron donors are utilized rapidly in the subsurface and therefore have a short to medium longevity in the field (approximately 4 to 12 weeks depending on the site). This implies that relatively frequent injections could be required in order to ensure adequate electron donor is available in the subsurface. Examples

of fast release electron donors include lactate, volatile fatty acids, alcohols, carbohydrates, sugars, and products from the dairy industry.

1.2 Slow Release Electron Donors

Slow release electron donors are those that are slowly fermented to molecular hydrogen. In general, these donors can have very high viscosities (up to and including being a solid) and relatively low solubilities, which can limit the ability to distribute them over large areas. This implies that numerous closely spaced injection points or trenches might be required in order to achieve adequate distribution. In addition, the relatively slow utilization can result in longer timeframes for establishment of appropriate redox conditions. Also, slow release donors generally do not enhance mass transfer from residual source areas to the extent that fast release donors do. In fact, some slow release donors (e.g. vegetable oil) can actually sequester contaminants because the hydrophobic chlorinated solvents can actually partition into the donor itself). Another consideration is that in general, slow release donors are more expensive than fast release donors on a unit cost basis.

However, the slower utilization of these donors also implies that slow release electron donors have much higher longevities in the subsurface, on the order of one to several years. This high longevity can result in a single application being sufficient to provide treatment at a site for several years. In addition, at sites with variable saturation, slow release donors can be especially long lived. Examples of slow release electron donors include edible oils (either as pure phase or as emulsified oils), Hydrogen Release Compound (HRC), and polymeric organic materials such as bark, mulch, and chitin.

1.3 Electron Donors Considered for the Site

The preferred approach for remediation at the Site involves in situ enhanced bioremediation (ISEB) consisting of continuous groundwater recirculation with pulsed donor addition and bioagumentation. Aqueous electron donors are best suited to this application because of the ability to achieve large-scale distribution, the more rapid establishment of reducing conditions, and the ability to achieve greater enhanced dissolution from the residual source area. In addition, most bioaugmentation applications to date have been performed using aqueous electron donors because of the need to stimulate rapid growth of the injected organisms. However, as a part of a phased remediation approach at the Site, slug injections may be performed at some time in the future. As a result, it was appeared appropriate to also consider a slow release electron donor.

Based on these factors, CDM included both aqueous and slow release donors in the donor evaluation process, with the intent of including 5 aqueous donors and 1 slow release donor in the laboratory treatability study. The following aqueous electron donors/donor groups were evaluated in this paper study phase of the donor evaluation:

- Ethanol and isopropanol
- Citric acid and sodium citrate
- Whey and lactose
- Lactate (as sodium lactate and lactic acid)
- Complex sugars (corn syrup and high fructose corn syrup)
- Molasses
- Glycerin/other polyols*
- Proprietary fermentation mother liquor*

*These are proprietary products preliminarily identified by JRW Bioremediation, LLC of Lenexa, Kansas (JRW) and are subject to a non-disclosure agreement between JRW and CDM.

It should be noted that the donors listed together in the same bullets are considered to be similar enough that in most cases, only one donor from each group would be evaluated in a laboratory study.

Given that injection wells are the only means available for emplacement (as opposed to hydraulic fracturing or trenching), only injectable slow release electron donors (i.e. emulsified oils) are considered for this application. The following slow release donors are considered in this paper study phase of the donor evaluation:

- Emulsified Oil Substrate (EOS)
- Newman Zone
- HRC-Advanced

2.0 Evaluation Criteria

The factors considered for the donor evaluation were grouped into the following four categories of criteria:

- Dechlorination Performance
- Administrative Requirements
- Handling and Storage Requirements

- Cost

These criteria are described further in the following subsections.

2.1 Dechlorination Performance

This category covers the aspects of the effectiveness of the various electron donors in stimulating complete dechlorination to ethene. Evaluation of these factors is based primarily on CDM and BRC experience, and to a lesser extent literature review and experience of others in the remediation industry. Factors considered in this criterion include:

- Success at other sites in stimulating complete dechlorination to ethene, particularly with bioaugmentation cultures
- Electron donor longevities, expressed as half lives for aqueous donors or advertised/known longevities in field applications for slow release donors
- Electron donor degradation products (if known)
- Biofouling/bioclogging potential

2.2 Administrative Requirements

This category covers site-specific administrative issues that would need to be addressed if a given electron donor was selected for use at the Site. Factors considered in this criterion include:

- Permits needed (along with estimated lead time)
- Licensing/patent issues
- Donor availability and supply
- Other miscellaneous issues

2.3 Handling and Storage Requirements

This category covers issues related to the handling, storage, and pre-treatment requirements for the various electron donors. For example, some donors may be able to be injected in the same form as they are delivered, while others may require dilution, mixing, or other pre-treatment steps. Factors considered in this criterion include:

- Donor characteristics (including solubility and solids content)
- Donor stability/shelf-life

- Mixing/filtration needs
- Onsite storage needs

2.4 Cost

This category covers the cost elements that would be incurred if a given electron donor was selected for use at the Site. Factors considered in this criterion include:

- Unit cost
- Cost per donor equivalent
- Unique capital costs (i.e. for special pre-treatment, handling, or storage needs)

While transportation costs are also an important consideration for overall project costs, these are expected to be similar for all donors being evaluated. Because of this, it was not a discriminating factor between the various donors at the paper evaluation stage.

3.0 Paper Evaluation Results

The electron donor paper study results are presented in the attached Tables 1 through 4. Each table contains the results of the donor evaluation for each of the four categories described in Section 2. Electron donors that were eliminated based on the evaluation in a given category are shaded in blue, and are not carried forward into the other categories. For example, corn syrup and high fructose corn syrup were eliminated based on dechlorination performance in Table 1, and are "grayed out" in the tables showing the other evaluation criteria. Overall, of the 17 donors considered in the paper study evaluation, the following five donors were recommended for the laboratory treatability study.

1. Citric acid or sodium citrate; the actual electron donor for both of these compounds is citrate. Pre-treatability study testing will be performed to determine mixing requirements, pH of resultant aqueous solutions, and potential for metals mobilization; one will be selected for the lab study.

2. Whey powder; whey will be evaluated for mixing requirements and solids content prior to the lab study.

3. Lactate (either as sodium lactate or lactic acid); as with citrate, the actual electron donor for both compounds is the same, so there is no need to test both donors.

4. JRW proprietary fermentation mother liquor; this will be evaluated for product stability and solids content prior to the lab study

5. Newman Zone – for its potential use during slug injections into existing wells at some point in the future (selected over EOS based on successful BRC experience at other sites and potentially slightly lower cost).

In addition to these five individual donors, CDM recommended that one electron donor be tested along with a proprietary JRW nutrient that has been shown to improve dechlorination efficiency by up to a factor of three. This nutrient would likely be added to whey powder, thus making the 6th donor condition to be studied.

4.0 Bioaugmentation Cultures

CDM performed a preliminary evaluation of potential bioaugmentation cultures for testing in the treatability study. Initially, it was planned to conduct testing of the six donor conditions with each of three bioaugmentation cultures. CDM discussed Site conditions with three vendors of bioaugmentation cultures – Bioremediation Consulting Inc, Shaw, and SiRem. Of these vendors, all indicated that they either currently have or could develop cultures that would perform well given the conditions at the Site. For example, Shaw's SDC-9™ culture has been shown to degrade chloroethenes, chloroethanes, and chloromethanes in Shaw internal testing. Also, SiREM was willing to provide KB-1 for testing at the Site. BCI was also willing to develop a culture specifically for the Site. However, BCI did not have production capacity or schedule to meet the needs of this large-scale project, and therefore was not a cost effective option for bioaugmentation at the Site. Because of this, the set of six donor conditions that were to be tested with a BCI bioaugmentation culture was run as unaugmented conditions.

Therefore, each of the six donor conditions will be tested with follows cultures:

- Shaw's SDC-9™ culture
- SiREM's KB-1™ culture
- Unaugmented donors

5.0 Conclusions and Recommendations

Based on the screening evaluation presented herein, CDM recommended that the laboratory treatability study be initiated to evaluate the following electron donors:

- Citrate
- Whey powder
- Lactate

- JRW proprietary fermentation mother liquor
- Whey powder plus JRW nutrient
- Newman Zone

Each of these donors was proposed to be tested with no bioaugmentation culture, with a culture from SiRem, and with a culture from Shaw. In addition, the microcosm would be spiked with 1,1,1-trichloroethane (1,1,1-TCA) and chloroform as appropriate to allow an assessment of the degradative capabilities of the cultures toward these compounds, as well as the extent to which these compounds inhibit chloroethene degradation. The spike concentrations would be selected to be representative of the site groundwater based on the most recent groundwater sampling data available at the time (which was March 2006). The laboratory treatability study would be conducted in accordance with the LARWQCB-approved testing plan provided in the Pre-Remediation Workplan (CDM, 2006) and modified as appropriate to the information provided in this document.

5.0 References

CDM. 2006. "Pre-Remediation Workplan, Boeing Realty Corporation , Former C-6 Facility, 19503 South Normandie Avenue, Los Angeles, California.". February 14.

French, J.H., A. Rossi, K.T. Kirk, D.B. Blackwelder, K.S. Sorenson, B. Rahm, L. Alvarez-Cohen, S. Le, M. Pound and P. Tamashiro. 2003. "Phased In Situ Biostimulation/Bioaugmentation Pilot Testing in a Coastal Aquifer." Proceedings of the Eighth International In-Situ and On-Site Bioremediation Symposium, Battelle Press, Columbus, OH. June.

Interstate Technology Regulatory Council (ITRC) 2005. Overview of In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones. BioDNAPL-1, Washington, DC. Interstate Technology & Regulatory Council, DNAPL team, available online at www.itrcweb.org

Evans, P.J. 2006. Personal Communication with Paul Hatzinger, Shaw. September 15.

Macbeth, T.W., L.O. Nelson, J.S. Rothermel, R.A. Wymore, and K.S. Sorenson, 2006. "Evaluation of Whey for Bioremediation of Trichloroethene Source Zones." *Bioremediation Journal*, 10(3):115–128.

Song, D.L., M.E. Conrad, Sorenson, K.S., and L. Alvarez-Cohen. 2002. "Stable Carbon Isotope Fractionation during Enhanced In-Situ Bioremediation of Trichloroethene." *Environmental Science and Technology*, 36(10):2262-2268.

Sorenson, K.S. 2002. "Enhanced Bioremediation for Treatment of Chlorinated Solvent Residual Source Areas," Chlorinated Solvent and DNAPL Remediation – Innovative Strategies for Subsurface Cleanup, ACS Symposium Series 837, American Chemical Society, Washington, D.C., pp. 119-131. http://www.clu-in.org/studio/napl_121002/59/32/32bw.pdf

Attachments:

Table 1 – Evaluation Results for Dechlorination Performance Criterion
Table 2 – Evaluation Results for Administrative Requirements Criterion
Table 3 – Evaluation Results for Handling and Storage Requirements Criterion
Table 4 – Evaluation Results for Donor Cost Criterion

Table 1
Former C-6 Facility
Results of Electron Donor Evaluation (Paper Study) - Groundwater Remediation
Evaluation Results for Dechlorination Performance Criterion

Donor	Degradation to Ethene	Donor Longevity	Primary Donor Degradation Products	Biofouling/Bioclogging Potential	Retained based on Dechlorination Criteria
Ethanol	Well documented at other sites	half life 15-30 days	VFAs (propionate, acetate)	has been observed at other sites, but can likely be mitigated by higher concentration pulse injections	**Yes**
Isopropanol	Less common than ethanol	expected half life 15-30 days	VFAs (propionate, acetate)	expected to be similar to ethanol	**Yes**
Citric acid	Increasing number of successful applications [1]	expected half life 15-30 days	unknown; likely VFAs	less likely than most other donors	**Yes**
Sodium Citrate	Increasing number of successful applications	expected half life 15-30 days	unknown; likely VFAs	less likely than most other donors	**Yes**
Whey	Increasing number of applications; CDM experience highly successful; good enhanced dissolution properties	half life 30-45 days	VFAs (propionate, acetate, butyrate)	some components of whey are rapidly utilized, which could cause fouling; however CDM has been successful in avoiding this in the past	**Yes**
Lactose	few field applications, although dechlorination would likely be similar to whey; little enhanced dissolution effects	expected half life 15-30 days	VFAs (propionate, acetate, butyrate)	similar to whey	No - degradation using whey would be similar; enhanced dissolution from source is better with whey
Sodium Lactate	widely used successfully; considered to be "universal donor"	half life 15-30 days	VFAs (propionate, acetate, butyrate)	many successful applications in the past without biofouling, including CDM experience	**Yes**
Lactic acid	less common than lactate, but very similar; pH drop may occur following injection	half life 15-30 days	VFAs (propionate, acetate, butyrate)	less likely than most other donors	**Yes**
Corn Syrup	few known applications	expected half life 10-20 days	unknown; likely VFAs	rapid utilization could lead to biofouling	No - unproven donor for chlorinated solvents; has rapid utilization and may cause biofouling
High Fructose Corn Syrup	few known applications	expected half life 10-20 days	unknown; likely VFAs	rapid utilization could lead to biofouling	No - unproven donor for chlorinated solvents; has rapid utilization and may cause biofouling
Molasses	widely used with mixed results; unsuccessful in previous applications at Site	half life 10-20 days	VFAs, alcohols, ketones	high potential - was a problem previously at C-6	No - previously failed at the Site
Glycerin	few known applications; initial testing by vendor shows poor dechlorination	expected half life 30-60 days	unknown; likely VFAs	unknown	No

Table 1
Former C-6 Facility
Results of Electron Donor Evaluation (Paper Study) - Groundwater Remediation
Evaluation Results for Dechlorination Performance Criterion

Donor	Degradation to Ethene	Donor Longevity	Primary Donor Degradation Products	Biofouling/Bioclogging Potential	Retained based on Dechlorination Criteria
Other polyols	few known applications; initial testing by vendor shows poor dechlorination	expected half life 30-60 days	unknown; likely VFAs	unknown	No
Proprietary fermentation mother liquor*	no field testing to date; initial testing by vendor showed significantly better performance than lactate	expected half life 15-30 days	unknown; likely VFAs	unknown	**Yes**
EOS	CDM experience successful	documented longevities of 1-2 years	VFAs (propionate, acetate, butyrate)	low potential given slow utilization	**Yes**
Newman Zone	increasing number of applications; several successful BRC applications	documented longevity of 1-2 years	VFAs (propionate, acetate, butyrate)	low potential given slow utilization	**Yes**
HRC-Advanced	new product; largely untested	advertised longevity of 2 years	lactic acid, VFAs (propionate, acetate, butyrate)	low potential given slow utilization	No - other products are similar and have been demonstrated at other sites

Notes:

VFAs - Volatile fatty acids

[1] - Evans,P.J. 2006. Personal Communication with Paul Hatzinger, Shaw. September 15

Table 2
Former C-6 Facility
Results of Electron Donor Evaluation (Paper Study) - Groundwater Remediation
Evaluation Results for Administrative Requirements Criterion

Donor	Permits	Licensing/Patents	Donor Availability and Supply	Other	Retained based on Administrative Criteria
Ethanol	Covered under general WDR (Order No. R4-2005-0030: Series 007); would also require L.A. City Fire Department permit, additional permit requirements from SCAQMD, and specially denatured alcohol (SDA) permit from the U.S. Bureau of Alcohol, Tobacco, and Firearms (ATF)	No issues	Widely available	Flammable substances viewed as highly unfavorable by BRC and tenants. Would require use of explosion proof equipment and construction	No - cost and performance of donor do not outweigh the permitting issues and concerns about tenant perception
Isopropanol	Covered under general WDR (Order No. R4-2005-0030: Series 007); would also require L.A. City Fire Department permit and additional permit requirements from SCAQMD	No issues	Widely available	Flammable substances viewed as highly unfavorable by BRC and tenants. Would require use of explosion proof equipment and construction	No - cost and performance of donor do not outweigh the permitting issues and concerns about tenant perception
Citric acid	Site-Specific WDR would be required	No issues	Widely available	Because citrate is a chelating agent, the potential for metals mobilization needs to be investigated; metals analysis can be included in the lab study if needed	**Yes**
Sodium Citrate	Site-Specific WDR would be required	No issues	Widely available	Because citrate is a chelating agent, the potential for metals mobilization needs to be investigated; metals analysis can be included in the lab study if needed	**Yes**
Whey	Covered under general WDR (Order No. R4-2005-0030: Series 007)	North Wind, Inc. has a patent pending for applications in source areas at injection concentrations greater than or equal to 1%. Procurement through JRW would include applicable license fees	JRW for patented application; other suppliers will be considered as appropirate		**Yes**
Lactose					No - Based on Table 1
Sodium Lactate	Covered under general WDR (Order No. R4-2005-0030: Series 007)	The Idaho National Laboratory has a patent on applications in source areas at injection concentrations at greater than or equal to 3%. Procurement through JRW would include applicable license fees.	JRW for patented application; other suppliers will be considered as appropirate		**Yes**
Lactic acid	Covered under general WDR (Order No. R4-2005-0030: Series 007)	No issues	several suppliers		**Yes**

Table 2
Former C-6 Facility
Results of Electron Donor Evaluation (Paper Study) - Groundwater Remediation
Evaluation Results for Administrative Requirements Criterion

Donor	Permits	Licensing/Patents	Donor Availability and Supply	Other	Retained based on Administrative Criteria
Corn Syrup					No - Based on Table 1
High Fructose Corn Syrup					No - Based on Table 1
Molasses					No - Based on Table 1
Glycerin					No - Based on Table 1
Other polyols					No - Based on Table 1
Proprietary fermentation mother liquor	Site-Specific WDR would be required; ; degradation products and metals content would need to be determined for permit	Proprietary product subject to NDA between JRW and CDM; further action would be required by JRW and BRC	JRW only		TBD pending NDA issues
EOS	Site-Specific WDR would be required	proprietary product available from one supplier	EOS remediation only		**Yes**
Newman Zone	Site-Specific WDR would be required	proprietary product available from one supplier	RNAS only - orders greater than 10,000 lbs may need 1 month lead time		**Yes**
HRC-Advanced					No - Based on Table 1

Notes:
NDA - Non-disclosure agreement
TBD - To be determined

Table 3
Former C-6 Facility
Results of Electron Donor Evaluation (Paper Study) - Groundwater Remediation
Evaluation Results for Handling and Storage Requirements Criterion

Donor	Donor characteristics	Donor Stability/Shelf life	Mixing/Filtration Needs	Onsite Storage Needs	Retained based on Handling and Storage Criteria
Ethanol					No - Based on Table 2
Isopropanol					No - Based on Table 2
Citric acid	solid phase; ~100% organic; delivered in drums or totes	shelf life of months	mixing may be needed; pre-treatability study evaluation required	depending on concentration, aqueous solution may have pH<2, and may require equipment capable of handling corrosives; also, given that citrate is a chelating agent, compatible containers need to be investigated	**Yes**; pH and mixing requirements will be tested prior to lab treatability study
Sodium Citrate	solid phase ~76% organic; delivered in drums or totes	shelf life of months	mixing may be needed; pre-treatability study evaluation required	aqueous solution pH ~2.5 to 4, so specialized equipment shouldn't be needed; also, given that citrate is a chelating agent, compatible containers need to be investigated	**Yes**; pH and mixing requirements will be tested prior to lab treatability study
Whey	solid phase ~87% organic; delivered in 1000 lb totes	shelf life of 1-2 years in solid form	can be mixed inline with a Venturi mixer capable of handling totes; does contain solids, so filtration might be needed	dry covered storage needed for totes	**Yes** - solids issue will be investigated during lab study
Lactose					No - Based on Table 1
Sodium Lactate	liquid phase 60% solution; delivered in drums, 275 gal totes, or ~40,000 lb tanker trucks	very stable; shelf life of months to years	completely soluble; can be mixed inline	dry covered storage needed for drums or totes; large tanks needed if tanker delivery is selected	**Yes**
Lactic acid	liquid phase 88% organic; delivered in drums, 275 gal totes, or ~40,000 lb tanker trucks	reactive; with proper storage, shelf life of months	completely soluble; can be mixed inline	pH <2 for stock solution; requires equipment capable of handling corrosives (i.e. pumps, tanks, etc).	**Yes**
Corn Syrup					No - Based on Table 1
High Fructose Corn Syrup					No - Based on Table 1
Molasses					No - Based on Table 1
Glycerin					No - Based on Table 1
Other polyols					No - Based on Table 1

Table 3
Former C-6 Facility
Results of Electron Donor Evaluation (Paper Study) - Groundwater Remediation
Evaluation Results for Handling and Storage Requirements Criterion

Donor	Donor characteristics	Donor Stability/Shelf life	Mixing/Filtration Needs	Onsite Storage Needs	Retained based on Handling and Storage Criteria
Proprietary fermentation mother liquor*	liquid phase ~40% organic (remainder is water); delivered in drums, totes, or tankers	stable; expected shelf life of weeks to months	completely soluble; can be mixed inline	dry covered storage needed for drums or totes; large tanks needed if tanker delivery is selected	**Yes**; solids content and product stability will be investigated during the lab study
EOS	liquid phase, delivered as ~50% emulsified oil; available as drums or 275 gal totes	stable emulsion; shelf life weeks to months	no field mixing or emulsification needed; can be mixed inline much like lactate	dry covered storage needed for totes	**Yes**
Newman Zone	liquid phase, delivered as ~50% emulsified oil; available as ~2000 lb totes	very stable emulsion; shelf life of 2 months if not refrigerated; shelf life is 1 yr if refrigerated	no field mixing or emulsification needed; can be mixed inline much like lactate	dry covered storage needed for totes	**Yes**
HRC-Advanced					No - Based on Table 1

Table 4
Former C-6 Facility
Results of Electron Donor Evaluation (Paper Study) - Groundwater Remediation
Evaluation Results for Donor Cost Criterion

Donor	Unit Cost for Materials	Budgetary Cost per Organic content	Unique capital costs	Retained based on Cost Criteria
Ethanol				No - Based on Table 2
Isopropanol				No - Based on Table 2
Citric acid	$.73/lb	$.73/lb	bulk solids handling equipment	**Yes**
Sodium Citrate	$.70/lb	$.92/lb	bulk solids handling equipment	**Yes**
Whey	$.39/lb	$.45/lb	bulk solids handling equipment	**Yes**
Lactose				No - Based on Table 1
Sodium Lactate	$.69/lb	$1.44/lb	based on donor content, will require larger storage capacity compared to other donors	**Yes**
Lactic acid	$.85/lb	$.97/lb	requires acid tanks and pumps	**Yes**
Corn Syrup				No - Based on Table 1
High Fructose Corn Syrup				No - Based on Table 1
Molasses				No - Based on Table 1
Glycerin				No - Based on Table 1
Other polyols				No - Based on Table 1
Proprietary fermentation mother liquor*	$.21/lb	$.55/lb	based on donor content, will require larger storage capacity compared to other donors	**Yes**
EOS	$1.13 - $1.60/lb	$2.26 - $3.20/lb	none	**Yes**
Newman Zone	$1.05 - $1.75/lb	$2.10- $3.50/lb	none	**Yes**
HRC-A				No - Based on Table 1

Notes:
Costs in this table do not include transportation costs (which are expected to be similar for all donors) or taxes.
Because whey is considered a commodity, unit costs can vary from approximately $.22/lb to $.45/lb

Appendix C

ELECTRON DONOR LABORATORY TREATABILITY STUDY

CDM

CDM

Appendix C

Electron Donor Laboratory Treatability Study Remediation of Volatile Organic Compounds Former C-6 Facility, Los Angeles, California

1.0 Introduction

Camp Dresser & McKee Inc (CDM) has prepared this report summarizing the laboratory treatability study conducted to evaluate electron donors and bioaugmentation cultures for remediation of volatile organic compound (VOC)-impacted groundwater at the Former C-6 Facility (Site). The primary contaminant of concern at this Site is trichloroethene (TCE) with 1,1-dichloroethene (1,1-DCE) as a secondary contaminant of concern. The study was conducted in general accordance with the CDM document titled "Pre-Remediation Workplan (CDM, 2006) which was approved by the Los Angeles Regional Water Quality Control Board (RWQCB) on February 23, 2006

The objectives of this study were as follows:

- Determine the efficiency of select electron donors and bioaugmentation cultures in achieving complete reductive dechlorination of TCE to ethene;
- Determine the potentially toxic effects of chloroform and 1,1,1-trichloroethane on reductive dechlorination of TCE; and
- Evaluate the life-time and shelf life of each of the electron donors.
- Evaluate factors affecting the selection including any mixing, filtration, or other pretreatment requirements.
- Evaluate donor stability and potential for precipitation or fermentation under ambient storage conditions.

Electron donors for this treatability study were selected based on the results of a background "paper" evaluation conducted by CDM (Appendix B of the main document) and included sodium citrate, whey, sodium lactate, proprietary JRW mother liquor, Newman Zone, and whey plus proprietary JRW nutrient. Except for Newman Zone, all the electron donors are fast-release electron donors. Newman Zone is a slow release electron donor and slowly ferments to molecular hydrogen. JRW mother liquor is a fermentation product and JRW nutrient is a proprietary nutrient; they were provided by JRW Bioremediation LLC of Lenexa, Kansas.

Two bioaugmentation cultures were also selected for this treatability study based on the CDM background "paper" evaluation. The Sirem KB-1™ culture was obtained from SiREM laboratory. The KB-1™ culture is a natural dechlorinating microbial consortium that contains phylogenetic relatives of *Dehalococcoides* ethenogenes (Major *et al.*, 2002). The Shaw SDC-9™ is also a natural dechlorinating culture, and was obtained from Shaw Environmental, Inc. This culture was enriched by Shaw from a Navy site to treat chlorinated solvent-contaminated aquifers. The SDC-9™ culture contains *Dehalococcoides* spp. (DHC) bacteria that degrade chlorinated solvents to ethene (www.shawgrp.com/bioaugmentation/technologybioaugmentation.aspx).

The following sections provide: a description of the treatability study methods; the results of the study along with a detailed discussion of the data; conclusions developed from the study; recommendations for donor and bioaugmentation culture selection and further action, as appropriate; and an economic analysis of capital and electron donor usage costs specific to the recommended donors.

2.0 Treatability Study Methodologies

2.1 Setup

The treatability study was conducted in CDM's environmental treatability laboratory in Bellevue, Washington. Groundwater samples for microcosm setup were collected by Avocet Environmental, Inc. (Avocet) on October 23rd, 2006 from the on-Site C-Sand monitoring well IRZCMW003 located at the Former Building 2 area of the Site. Two soils samples were also collected by Avocet on October 24th and 25th from the B-sand and C-sand aquifers, respectively, for microcosm setup during installation of well MWC024 at the Former Building 2 area of the Site. Two 12-inch-long samples were collected from each of three intervals, two in the B-Sand (64.5 to 66.5 feet below ground surface [bgs] and 68 to 70 feet bgs) and one in the C-Sand (114.5 to 116.5 feet bgs). Detailed information regarding sample collection and handling procedures are included in Appendix A of the main document.

Table 1 presents the microcosm set-up. These microcosms were set up between October 25 and 30, 2006. Microcosms were constructed in duplicate in serum bottles in an anaerobic chamber with a nitrogen atmosphere. Each microcosm contained 50 grams (g) of soil sample (homogenized mixture of B-Sand and C-Sand soil) and 150 milliliters (mL) of groundwater sample. Microcosms were sealed with thick butyl rubber stoppers and aluminum crimp tops. Electron donors were added to microcosms as described in Table 1. The bottles were then removed from the anaerobic chamber. Any residual oxygen in the microcosms was allowed to be depleted by aerobes in the soil prior to the addition of bioaugmentation cultures as described in Table 1. Microcosms were then pressurized with ultra high purity nitrogen to 5 pounds per square inch (psi). Each microcosm was spiked with approximately 6,000 micrograms per liter (µg/L) of TCE, 450 µg/L of chloroform (CF), and 100 µg/L of 1,1,1-trichloroethane (TCA). Following baseline sampling and analysis, microcosms were re-spiked with 4,300 µg/L of TCE, 190 µg/L of CF, and 66 µg/L of TCA because observed

concentrations were less than intended. Microcosms were stored upside down in the dark at room temperature (16°C to 22°C).

2.2 Laboratory Sampling and Analysis

A total of seven sampling events were conducted between November 1, 2006 and March 13, 2007. Sampling frequency was on a biweekly basis for the first four sampling events, and decreased to a monthly basis for the last three sampling events. For each sampling event, the following analyses were performed:

- pH – measured with conventional pH meter.
- Sulfate (SO_4) – measured with Hach DR/2010 Spectrophotometer (Method 8051)
- Chemical Oxygen Demand (COD) – measured with Hach DR/2010 Spectrophotometer (Method 8000)
- VOCs – Purge and trap sampling and analysis by gas chromatography with flame ionization detection.
- Methane, Ethane, and Ethene – Headspace sampling and analysis by gas chromatography with flame ionization detection.

The initial VOC analysis was conducted by OnSite Environmental of Redmond, Washington because of equipment failure associated with the CDM GC. Carbon dioxide (CO_2) and volatile fatty acids (VFAs) analyses were also performed at the end of the study. CO_2 was sampled in the headspace and measured with gas chromatography with thermal conductivity detection. Liquid samples were sent to Microseeps, Inc. for VFA analysis.

3.0 Treatability Study Results and Discussion

3.1 TCE Biodegradation

Figures 1 to 4 show TCE biodegradation in the microcosms over time. Figure 1 shows the sterile and non-sterile control microcosms with no added electron donor or bioaugmentation culture. Figures 2, 3, and 4 show microcosms with various electron donors with no bioaugmentation, with Sirem KB-1™ culture, and with Shaw SDC-9™ culture, respectively. The control microcosms confirm that significant TCE degradation was not observed without electron donor addition. The increase in TCE concentration on Day 16 was due to the second addition of VOCs. The gradual decline in TCE concentrations was attributable to abiotic losses and/or analytical variability. Table 2 summarizes all findings.

3.2 Electron Donor Effects

Table 2 shows that 10 microcosms transformed TCE to vinyl chloride (VC) in 31-49 days, which is the fastest of all microcosms. Nine of these microcosms contained whey or lactate. It

is therefore concluded that whey and lactate had the fastest response times with respect to transformation to VC. Microcosms with whey, lactate, and Newman Zone were the most effective with respect to complete reductive dechlorination of TCE to ethene – eight out of the nine microcosms demonstrating complete reductive dechlorination contained whey, lactate, or Newman Zone. Sodium lactate promoted the fastest TCE to ethene conversion in 49-65 (bottle 17A) and 65-93 (bottle 17B) days. Sodium lactate appears to be the fastest electron donor in driving complete TCE to ethene dechlorination, although two Newman Zone and three whey microcosms also achieved dechlorination to ethene in 65-93 days.

3.3 Bioaugmentation Culture Effects

Eight out of 12 microcosms inoculated with Shaw SDC-9™ demonstrated complete TCE dechlorination to ethene in less than 134 days. Seven out of the eight Shaw SDC-9 ™ microcosms containing whey, lactate, or Newman Zone demonstrated complete reductive dechlorination to ethene. On the other hand, only one out of twelve microcosms inoculated with Sirem KB-1 ™ bioaugmentation culture demonstrated complete reduction of TCE to ethene in the same amount of time.

None of the microcosms without bioaugmentation achieved complete TCE to ethene conversion. Conversion to VC was observed in 11 out of 12 of these microcosms. This result is consistent with groundwater data for previously biostimulated locations at the Site, which showed that dechlorination of TCE may have stalled at VC. This suggests that bioaugmentation is a requirement for complete reduction of TCE to ethene within a reasonable time.

3.4 Gas Production

Headspace analysis was used to estimate gas production in the microcosms (Figures 9 to12). Additional CO_2 and methane analyses were performed on selected microcosms (Table 3) on day 144, subsequent to the last sampling event. Results show minimal (i.e., less than 0.5% methane in the headspace) methane production in most microcosms (i.e., both unbioaugmented and bioaugmented) and minimal CO_2 production in all microcosms. In Shaw culture microcosms amended with whey, sodium lactate, or Newman Zone, relatively greater methane production was observed (i.e., 2 to 5% methane in the headspace). In one Sirem culture microcosm amended with whey plus nutrient, relatively greater methane production was observed (i.e., 3 to 4% methane in the headspace. Thus gas production with the Shaw culture and lactate or whey does not appear to be significant. Gas production with the Shaw culture and Newman Zone may be significant.

3.5 CF and TCA Toxicity Effects

Previous unpublished data provided by Shaw have shown that the SDC-9™ culture is capable of chloroform and TCA degradation. In this study, chloroform was degraded to below detection limit in microcosms bioaugmented with Shaw SDC-9™ culture and amended with sodium lactate and Newman Zone (Table 2). TCE was also degraded completely to ethene in

these microcosms. During the final sampling event, chloroform was present in microcosms containing Shaw culture and whey plus nutrient. These microcosms also achieved complete TCE to ethene conversion. This demonstrates that in addition to Shaw's finding that the SDC-9™ culture is capable of chloroform degradation, it is also capable of achieving complete TCE degradation in the presence of chloroform. In contrast, during the final sampling event in microcosms with Sirem KB-1 ™ culture, chloroform was present in all but one bottle. Notably, this lone microcosm with no chloroform was also the only microcosm that was able to achieve complete reductive dechlorination of TCE to ethene. Based on these observations, it is apparent that the Shaw SDC-9 ™ culture was relatively more resistant than the Sirem KB-1 ™ culture to the toxicity or other form of inhibition associated with the added chloroform, either through its ability to transform CF, or its ability to reductively dechlorinate TCE to ethene in its presence.

3.6 Electron Donor Longevity

COD levels remained relatively constant throughout the study, even as TCE was being completely reduced (Figures 5 to 8). Microcosm gas production (Figures 9 to 12) showed insignificant methane production except in a few microcosms as noted in Section 3.4. Based on these observations, CDM's hypothesis for the lingering high levels of COD was that the carbon sources added to the microcosms were not being converted completely into methane and carbon dioxide (CO_2); rather, they were being partially fermented to VFAs. This partial degradation could provide sufficient electrons to promote reductive dechlorination but may not lead to significant COD reduction. To evaluate this hypothesis, 10 microcosm bottles were selected for CO_2 and VFA analysis subsequent to the last sampling round on day 144. These results are presented in Table 3. Table 3 demonstrates that the electron donors were partially fermented to various VFAs, and that by taking VFAs and CO_2 into account, the COD recovery is close to 100% for all microcosms except those with Newman Zone. Newman Zone is known to be adsorbed to soil, so low COD recovery was expected. Total organic carbon (TOC) recovery of close to 100% for all microcosms except Newman Zone further validated the hypothesis. The following paragraphs discuss the longevity of sodium lactate, Newman Zone, and whey:

Sodium lactate

Based on the VFA analysis (Table 3), five out of six lactate-amended microcosms contained significant amount of propionic acid five months after the donors were injected. In the remaining microcosm (17A), acetic acid was the major VFA instead of propionic acid. Combined with the fact that microcosm 17A achieved complete TCE to ethene dechlorination in 49 to 65 days, it was estimated that sodium lactate could potentially have a longevity in the aquifer of at least two months and possibly longer than five months, which is longer than what is typically observed for lactate. These longevity estimates are believed to be due to the persistence of the propionate and acetate that are derived from the lactate. That being said, it is possible that propionate and acetate would be degraded more quickly in the field than was

seen in the lab study. Because of this, the longevity of lactate would have to be validated during the pilot study.

Newman Zone

Since Newman Zone is an emulsified oil and it is adsorbed in the soil, a carbon balance could not be accurately performed. However, based on its usage at other sites, the life span of Newman Zone in soil is typically estimated to be one to two years.

Whey

Analyses for VFAs were not performed for microcosms amended with whey because whey is not a pure compound and electron balance calculations using whey would have been overly complicated for the scope of this study. However, since the COD changes over time of whey were similar to those of sodium lactate, it is assumed that the life span of whey is similar to that of sodium lactate. However, previous CDM experience suggests that whey may have a longer life span than sodium lactate.

3.7 Electron Donor Solubility and Shelf Life

The longevities and shelf life of sodium lactate, whey, and Newman Zone were evaluated by placing solutions containing these materials in bottles exposed to air and allowing them to stand at room temperature during the treatability study. Shelf life and other properties of each electron donors are presented in Table 4. These data indicate that sodium citrate, sodium lactate, and Newman Zone were stable and the other electron donors were perishable (i.e. biofilms growing in solution). However, it should be noted that the whey used in this study (and the whey that would be used in the field) is delivered to the site in powdered form rather than as a solution. The powdered form of whey has a shelf life of up to 2 years based on CDM experience.

All electron donors were completely soluble except whey and JRW nutrient. Previous studies indicated that a 10% whey solution contained about 23,000 mg/L total suspended solids (MacBeth et al., 2006). While this concentration is relatively high, CDM experience has been that injection of such whey solutions containing suspended solids has not resulted in well or aquifer plugging. Additionally, the solids may promote longevity of the whey. JRW nutrient at 1 grams per liter (g/L) did not go into solution even with vigorous mixing and heating, indicating limited solubility compared to other electron donors.

3.8 Supplemental Data

Supplemental data is provided in Attachment A (Figures 1A through 8A) and consist of pH and sulfate data for the various microcosms.

4.0 Economic Analysis

Based on the lab study results, both lactate and whey are expected to perform well in the field. While injection of whey does involve more manual labor and more equipment (e.g., handling and mixing equipment) than lactate, it offers the potential for significant cost savings over lactate. This cost savings is due to the lower material costs and more electron donor content for whey compared to lactate. As an example, for a 50 gallon per minute (gpm) biorecirculation system with an injection frequency of 10% (approximately 17 hours a week), using whey would cost approximately 50% less than using lactate even considering the additional labor costs to manually operate the whey mixing equipment. These costs includes material costs and labor costs specific only to donor handling and do not include the capital costs for whey handling and mixing equipment. However, even if capital costs for whey mixing and handling equipment are included, the costs are estimated to be still 33% less than lactate for this scenario. These savings would increase substantially as the scale of the application increases. One thing to note is that the cost of whey ($0.87/lb) is highly volatile and will affect the total costs; however, the volatility is unlikely to change the conclusion that whey is more cost-effective than lactate.

In addition to the above economic advantages, it has been shown at other sites that whey is able to enhance the dissolution of contaminants from the residual source at a faster rate than lactate (MacBeth et al., 2006). This can result in a shorter remediation timeframes.

5.0 Conclusions

The following conclusions were developed based on the results of this study:

- Whey, sodium lactate, and Newman Zone show the most promise as potential electron donors for use at the Site. Complete reductive dechlorination of TCE to ethene was observed in SDC-9™-bioaugmented microcosms with these donors.

- Sodium lactate was the fastest in achieving complete reductive dechlorination of TCE to ethene. It potentially has a life span in the Site aquifer of at least two months and possibly greater than five months, based on its fermentation to acetate and propionate. It had a shelf life of greater than five months.

- Whey exhibited the fastest response time in terms of TCE to VC conversion. It was capable of driving complete TCE to ethene dechlorination, although not as fast as lactate. It is expected to have an aquifer life span similar to that of sodium lactate. Whey was not completely soluble and filtration may be required. However previous CDM experience with whey indicated that filtration is not required. Therefore CDM recommends that whey be injected unfiltered and the potential effects of plugging being monitored during the pilot test. If plugging becomes an issue, filtration of whey or use of lactate can be implemented across the site. Once in solution, whey is perishable and had a shelf life of less than two

months based on CDM experience. Powdered whey, however, has a shelf-life of two years based on CDM experience, as previously indicated in Section 3.7.

- Newman Zone performed consistently. It was capable of driving complete TCE to ethene dechlorination and typically has a long aquifer life span of one to two years and possibly longer. It had a shelf life of greater than five months.

- The addition of JRW nutrient may have slightly improved the performance of microcosms with whey as electron donor. It is, however, poorly soluble.

- The indigenous microbial community (i.e., microcosms without bioaugmentation) drove dechlorination of TCE to VC, but not to ethene. This is consistent with field observations in biostimulated areas at the Site and provides further evidence that bioaugmentation will be required to achieve complete dechlorination to ethene in a reasonable timeframe.

- Shaw SDC-9™ culture had the ability to utilize a wide range of electron donors and achieve complete reductive dechlorination of TCE to ethene. Based on the data collected during this study, it was relatively resistant to chloroform and even appears to be capable of chloroform transformation. This is consistent with data provided by Shaw from their own studies (Unpublished data provided to CDM by Dr. Robert Steffan of Shaw).

- Sirem KB-1™ culture appeared to be sensitive to chloroform. It could potentially achieve complete reductive dechlorination of TCE to ethene with no chloroform present.

- Partial fermentation of electron donors was observed in all microcosms selected for VFA analysis. It can therefore be concluded that, although COD analyses showed almost constant values throughout the study, electron donor utilization was in fact occurring. VFA analysis provided good COD and TOC recoveries and was an adequate tool for electron donor concentration assessment.

  As indicated in Section 3.6, whey was not selected for VFA analysis because of impurities in whey that would have overly complicated electron balance calculations.

- Gas production in most of the microcosms was less than expected. This suggests that gas blockage during electron donor injection in the field is not likely to be a significant issue with these electron donors. It should be noted, however, that Newman Zone produced the greatest amount of methane compared to other electron donors.

6.0 Recommendations

The following recommendations were developed based on the results of this study:

- Based on the lab study results and the economic analysis presented here, it is recommended that whey be used initially for the pilot study, and lactate be used if

logistical issues (i.e. mixing, storage, handling, etc) or technical performance issues (e.g., solids plugging of injection wells) are encountered with whey.

- Newman Zone is recommended for slug injections if planned at the Site. Methane production should be taken into account and at the minimum monitored in the field when using Newman Zone.
- Sodium citrate and JRW mother liquor were inconsistent performers and are not recommended.
- Shaw SDC-9™ culture is the recommended choice for bioaugmentation.
- Sirem KB-1™ culture is not recommended for bioaugmentation at this site.
- JRW nutrient should not be used unless it can be modified by the manufacturer to increase its solubility.

7.0 References

CDM. 2006. "Pre-Remediation Workplan, Boeing Realty Corporation , Former C-6 Facility, 19503 South Normandie Avenue, Los Angeles, California.". February 14.

Major DW *et al*. 2002. Field Demonstration of Successful Bioaugmentation To Achieve Dechlorination of Tetrachloroethene To Ethene. *Environ Sci Technol*. **36**(23):5106-5116.

Macbeth, T.W., L. Nelson, J.S. Rothermel, R.A. Wymore, and K.S. Sorenson Jr. 2006. Evaluation of Whey for Bioremediation of Trichloroethene Source Zones. *Bioremediation J.* **10**(3) :115-128.

8.0 Limitations

It should be noted that many of the conclusions from this study (especially comparisons of electron donors and cultures) are site-specific because they depend on the indigenous microbial community, groundwater geochemistry, soil chemistry, and contaminant mixture. Therefore some of the findings of this treatability study will not be transferable to other sites.

9.0 Attachments

Tables

Table 1 – Treatability Study Design
Table 2 – Summary of Results
Table 3 – COD and TOC Summary
Table 4 – Shelf Life of Electron Donors

Figures

Figure 1 – TCE Degradation in Control Microcosms
Figure 2 – TCE Degradation in Microcosms with No Bioaugmentation
Figure 3 – TCE Degradation in Microcosms with Sirem KB-1 Bioaugmentation Culture
Figure 4 – TCE Degradation in Microcosms with Shaw SDC-9 Bioaugmentation Culture
Figure 5 – COD- Control Microcosms
Figure 6 – COD- Microcosms with no Bioaugmentation
Figure 7 – COD- Microcosms with Sirem KB-1 Bioaugmentation Culture
Figure 8 – COD- Microcosms with Shaw SDC-9 Bioaugmentation Culture
Figure 9 – Headspace Gas Production in Control Microcosms
Figure 10– Headspace Gas Production in Microcosms with no Bioaugmentation
Figure 11– Headspace Gas Production in Microcosms Bioaugmented with Sirem KB-1 Culture
Figure 12– Headspace Gas Production in Microcosms Bioaugmented with Shaw SDC-9 Culture

Attachment A – Supplemental Data

Figure 1A – pH- Control Microcosms
Figure 2A – pH- Microcosms with no Bioaugmentation
Figure 3A – pH- Microcosms with Sirem KB-1 Bioaugmentation Culture
Figure 4A – pH- Microcosms with Shaw SDC-9 Bioaugmentation Culture
Figure 5A – SO4- Control Microcosms
Figure 6A – SO4- Microcosms with no Bioaugmentation
Figure 7A – SO4- Microcosms with Sirem KB-1 Bioaugmentation Culture
Figure 8A – SO4- Microcosms with Shaw SDC-9 Bioaugmentation Culture

Table 1 - Treatability Study Design

Bottle[a,b]	Culture[c]	Sterile[d]	Donor	Donor Concentration (g/L)	Initial Target Concentrations		
					TCE (µg/L)	CF (µg/L)	TCA (µg/L)
1	None	Yes	None	NA	6000	450	100
2	None	No	None	NA	6000	450	100
3	None	No	Sodium citrate	1	6000	450	100
4	None	No	Whey powder	1	6000	450	100
5	None	No	Sodium lactate	1	6000	450	100
6	None	No	JRW mother liquor[e]	1	6000	450	100
7	None	No	Newman Zone	1	6000	450	100
8	None	No	Whey + JRW nutrient[f]	1 + 0.1	6000	450	100
9	Sirem KB-1	No	Sodium citrate	1	6000	450	100
10	Sirem KB-1	No	Whey powder	1	6000	450	100
11	Sirem KB-1	No	Sodium lactate	1	6000	450	100
12	Sirem KB-1	No	JRW mother liquor[e]	1	6000	450	100
13	Sirem KB-1	No	Newman Zone	1	6000	450	100
14	Sirem KB-1	No	Whey + JRW nutrient[f]	1 + 0.1	6000	450	100
15	Shaw SDC-9	No	Sodium citrate	1	6000	450	100
16	Shaw SDC-9	No	Whey powder	1	6000	450	100
17	Shaw SDC-9	No	Sodium lactate	1	6000	450	100
18	Shaw SDC-9	No	JRW mother liquor[e]	1	6000	450	100
19	Shaw SDC-9	No	Newman Zone	1	6000	450	100
20	Shaw SDC-9	No	Whey + JRW nutrient[f]	1 + 0.1	6000	450	100

footnotes:

[a]Each bottle was setup in duplicate and labelled A and B

[b]Each bottle contains 50 grams of soil and 150 ml of groundwater from the C-6 Facility.

[c]Microcosms were inoculated with 1.5ml of Bioaugmentation culture estimated to contain 10^8 cells / ml.

[d]Sterilization was conducted by autoclaving at 20 psig for 20 minutes two days in succession.

[e]JRW mother liquor is a fermentation product provided by JRW.

[f]JRW nutrient is a proprietary nutrient provided by JRW.

Abbreviations:

NA = Not applicable

TCE = Trichloroethene

CF = Chloroform

TCA = 1,1,1-Trichloroethane

g/L = grams per liter

µg/L = micrograms per liter

ml = milliliter

Table 2 - Summary of Results

Bottle[a]	Culture	Donor	Duplicate	Observed time for reductive dechlorination of TCE (Days):			Final Concentrations		
				to cis-1,2-DCE	to Vinyl Chloride	to Ethene	TCE (µg/L)	CF (µg/L)	TCA (µg/L)
1	None	None	A	*>134*	*>134*	*>134*	6155	363	*<80*
			B	*>134*	*>134*	*>134*	5687	253	*<80*
2	None	None	A	*>134*	*>134*	*>134*	582	279	*<80*
			B	*>134*	*>134*	*>134*	2808	652	*<80*
3	None	Sodium citrate	A	**31**	**134**	*>134*	*<50*	315	*<80*
			B	**31**	*>134*	*>134*	*<50*	916	*<80*
4	None	Whey powder	A	**16**	**49**	*>134*	*<50*	239	*<80*
			B	**16**	**65**	*>134*	*<50*	254	*<80*
5	None	Sodium lactate	A	**31**	**93**	*>134*	*<50*	275	*<80*
			B	**31**	**93**	*>134*	*<50*	283	*<80*
6	None	JRW mother liquor	A	**31**	**93**	*>134*	*<50*	286	*<80*
			B	**31**	**93**	*>134*	*<50*	306	*<80*
7	None	Newman Zone	A	**31**	**134**	*>134*	*<50*	195	*<80*
			B	**31**	**93**	*>134*	*<50*	171	*<80*
8	None	Whey + JRW nutrient	A	**16**	**49**	*>134*	*<50*	308	*<80*
			B	**16**	**49**	*>134*	*<50*	299	*<80*
9	Sirem KB-1	Sodium citrate	A	**31**	**134**	*>134*	*<50*	359	*<80*
			B	**31**	**134**	*>134*	*<50*	340	*<80*
10	Sirem KB-1	Whey powder	A	**31**	**49**	*>134*	*<50*	265	*<80*
			B	**16**	**49**	*>134*	*<50*	283	*<80*
11	Sirem KB-1	Sodium lactate	A	**16**	**65**	*>134*	*<50*	300	*<80*
			B	**16**	**65**	*>134*	*<50*	292	*<80*
12	Sirem KB-1	JRW mother liquor	A	**31**	**65**	*>134*	*<50*	310	*<80*
			B	**16**	**65**	*>134*	*<50*	84	*<80*
13	Sirem KB-1	Newman Zone	A	**16**	**93**	*>134*	*<50*	209	*<80*
			B	**16**	**93**	*>134*	*<50*	180	*<80*
14	Sirem KB-1	Whey + JRW nutrient	A	**31**	**49**	**93**	<50	*<50*	*<80*
			B	**31**	**49**	*>134*	*<50*	278	*<80*
15	Shaw SDC-9	Sodium citrate	A	**16**	**93**	*>134*	*<50*	317	*<80*
			B	**16**	**93**	*>134*	*<50*	400	*<80*
16	Shaw SDC-9	Whey powder	A	**16**	**65**	*>134*	*<50*	329	*<80*
			B	**16**	**65**	**93**	<50	*<50*	*<80*
17	Shaw SDC-9	Sodium lactate	A	**16**	**49**	**65**	<50	*<50*	*<80*
			B	**16**	**49**	**93**	<50	*<50*	*<80*
18	Shaw SDC-9	JRW mother liquor	A	**31**	**49**	**134**	<50	292	*<80*
			B	**31**	*>134*	*>134*	*<50*	940	*<80*
19	Shaw SDC-9	Newman Zone	A	**16**	**93**	**93**	<50	*<50*	*<80*
			B	**16**	**93**	**93**	<50	*<50*	*<80*
20	Shaw SDC-9	Whey + JRW nutrient	A	**16**	**65**	**93**	<50	210	*<80*
			B	**16**	**65**	**134**	<50	250	*<80*

footnotes:

[a]Each bottle was setup in duplicate and labelled A and B

Abbreviations:

TCE = Trichloroethene

cis-1,2-DCE = cis-1,2-dichloroethene

CF = Chloroform

TCA = Trichloroethane

Table 3 - COD and TOC Summary

					Methane Production	CO_2 Production[b]			Volatile Fatty Acids Production[c]					COD						TOC		
Bottle	Donor	Culture	Rep	Initial Donor	Methane	$CO_{2,aq}$	$CO_{2,g}$	Total CO_2	Acetic	Butyric	Lactic	Propionic	Pyruvic	Initial Observed COD	Final Observed COD	Observed COD % Recovery	Intial Calculated COD[d]	Final Calculated COD[e]	Calculated COD % Recovery	Initial Calculated TOC[f]	Final Calculated TOC[g]	TOC % Recovery
				mmol[a]	mmol[a]	mmol[a]			mmol[a]					mmol[a]	mmol[a]	%	mmol[a]	mmol[a]	%	mmol[a]	mmol[a]	%
5	Sodium lactate	None	*A*	1.339	0.0036	0.2649	0.0517	0.317	0.699	0.003	0	0.729	0	4.69	4.34	92%	4.02	3.97	99%	4.02	3.92	98%
5	Sodium lactate	None	*B*	1.339	0.0064	0.4861	0.0917	0.578	0.724	0.005	0	0.729	0	4.73	4.44	94%	4.02	4.02	100%	4.02	4.24	106%
11	Sodium lactate	Sirem KB-1	*A*	1.339	0.0064	0.3683	0.0771	0.445	0.624	0.004	0	0.709	0	4.45	4.45	100%	4.02	3.75	93%	4.02	3.84	96%
11	Sodium lactate	Sirem KB-1	*B*	1.339	0.0067	0.3883	0.0758	0.464	0.624	0.004	0	0.709	0	4.41	4.39	99%	4.02	3.75	93%	4.02	3.86	96%
17	Sodium lactate	Shaw SDC-9	*A*	1.339	0.1988	0.3750	0.0897	0.465	1.524	0.007	0	0.172	0	5.02	4.66	93%	4.02	3.69	92%	4.02	4.26	106%
17	Sodium lactate	Shaw SDC-9	*B*	1.339	0.0131	0.3906	0.0860	0.477	0.949	0.008	0	0.729	0	4.95	5.20	105%	4.02	4.49	112%	4.02	4.61	115%
15	Sodium citrate	Shaw SDC-9	*A*	0.510	0.0067	0.4810	0.0729	0.554	0.999	0.016	0	0.004	0	2.40	2.63	110%	2.30	2.10	91%	3.06	2.64	86%
15	Sodium citrate	Shaw SDC-9	*B*	0.510	0.0068	0.4190	0.0623	0.481	1.049	0.005	0	0.002	0	2.45	2.48	101%	2.30	2.13	93%	3.06	2.61	85%
19	Newman Zone	Shaw SDC-9	*A*	0.170	0.5035	0.5686	0.0894	0.658	0.092	0.073	0	0.006	0	1.02	1.58	155%	6.28	0.57	9%	9.67	1.66	17%
19	Newman Zone	Shaw SDC-9	*B*	0.170	0.4977	0.4264	0.0722	0.499	0.072	0	0.233	0.007	0	0.94	2.34	250%	6.28	0.87	14%	9.67	1.86	19%

footnote:

[a]All concentrations are presented in mmol / microcosm bottle

[b]CO2 concentrations are calculated based on Headspace CO2 concentrations

[c]Odor and visual observations were performed on the stock solutions that have been stored on shelf for the indicated length of time.

[d]Initial calculated COD was calculated based on initial donor COD concentrations

[e]Final calculated COD was calculated based on CH4, CO2, and volatile fatty acids COD calculations

[f]Initial calculated TOC was calculated based on initial donor TOC concentration

[g]Final calculated TOC was calculated based on CH4, CO2, and volatile fatty acids TOC calculations

Abbreviations:

$CO_{2,aq}$ = Carbon Dioxide in the aqueous phase (including bicarbonate and carbonic acid)

$CO_{2,g}$ = Carbon Dioxide in the gas phase

COD = Chemical Oxygen Demand

TOC = Total Organic Carbon

mmol = milimoles (per microcosm bottle)

Table 4 - Shelf Life of Electron Donors

Donor / Nutrient	Stock Solution Concentration (g/L)	Solubility[a]	Time on Shelf	Observed Odor Changes[b]	Observed Visual Changes[b]
Sodium Citrate	100	5	5 months	None	None
Whey	100	3	1.5 months	None	Contains floating film (fungus)
Sodium Lactate	100	5	5 months	None	None
JRW Mother Liquor	400	5	5 months	None	Contains floating film, sediments
Newman Zone	500	5	5 months	None	None
JRW Nutrient	1	1	5 months	Stronger, sweeter, and more acidic odor	Contains floating film

footnote:

[a]Solubility observation at stock solution concentration:
1 - Insoluble
2 - Slightly Soluble
3 - Soluble with solids settling
4 - Soluble
5 - Soluble with little mixing

[b]Odor and visual observations were performed on the stock solutions that have been stored on shelf for the indicated length of time and compared to initial observations when the stock solutions were freshly made

Abbreviations:
g/L = grams per liter

Figure 1 - TCE Degradation in Control Microcosms

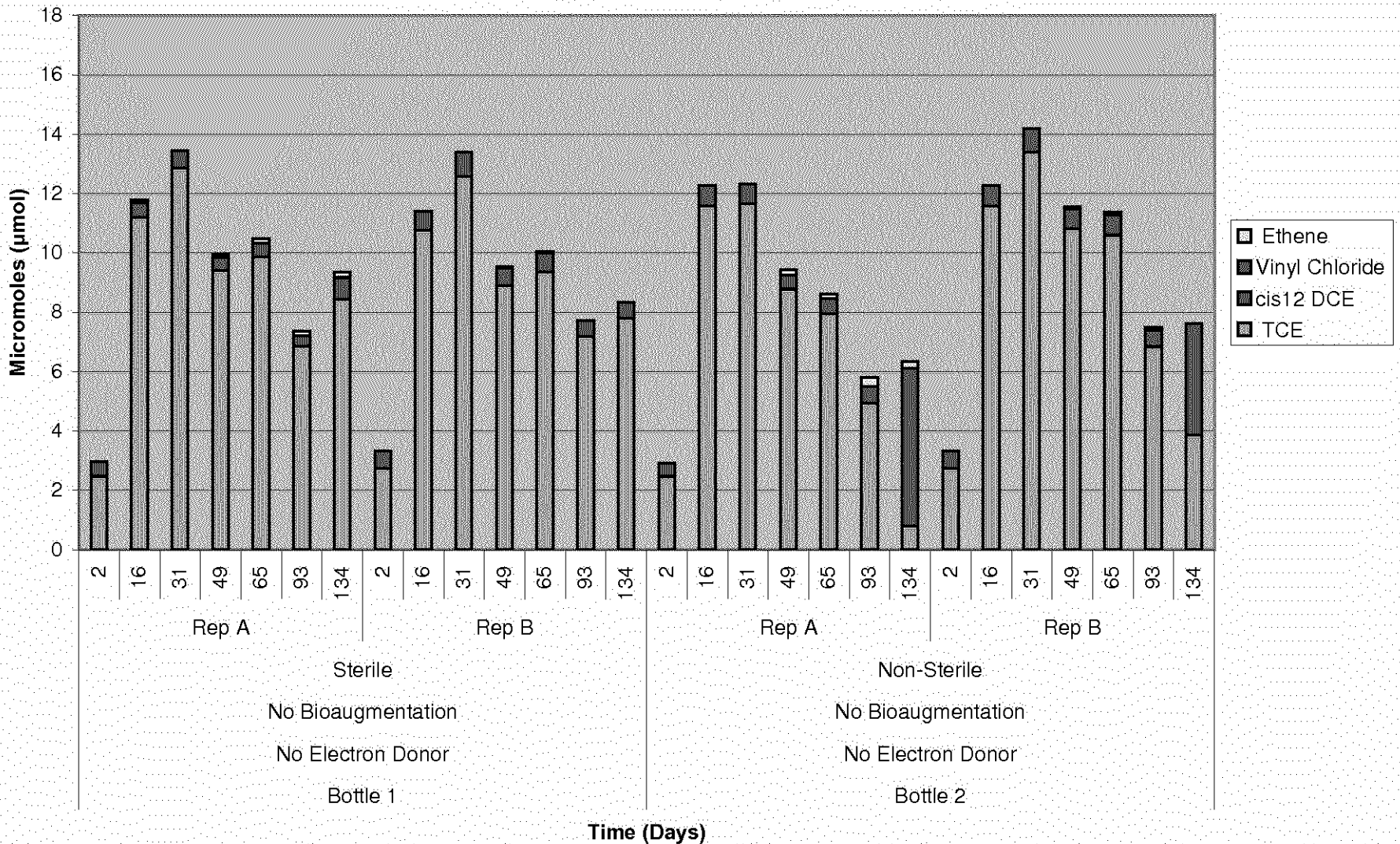

Figure 2 - TCE Degradation in Microcosms with No Bioaugmentation

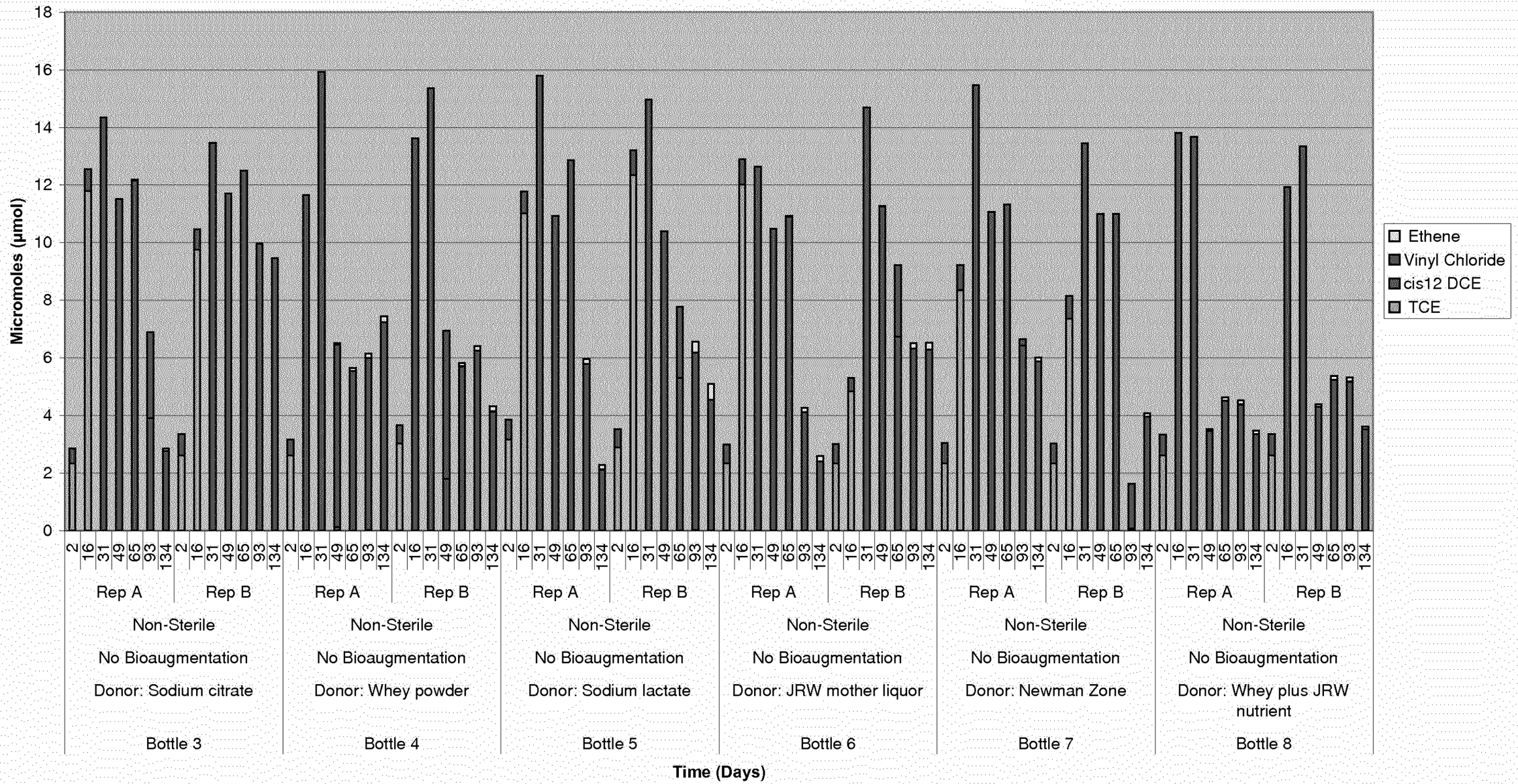

Figure 3 - TCE Degradation in Microcosms with Sirem KB-1 Bioaugmentation Culture

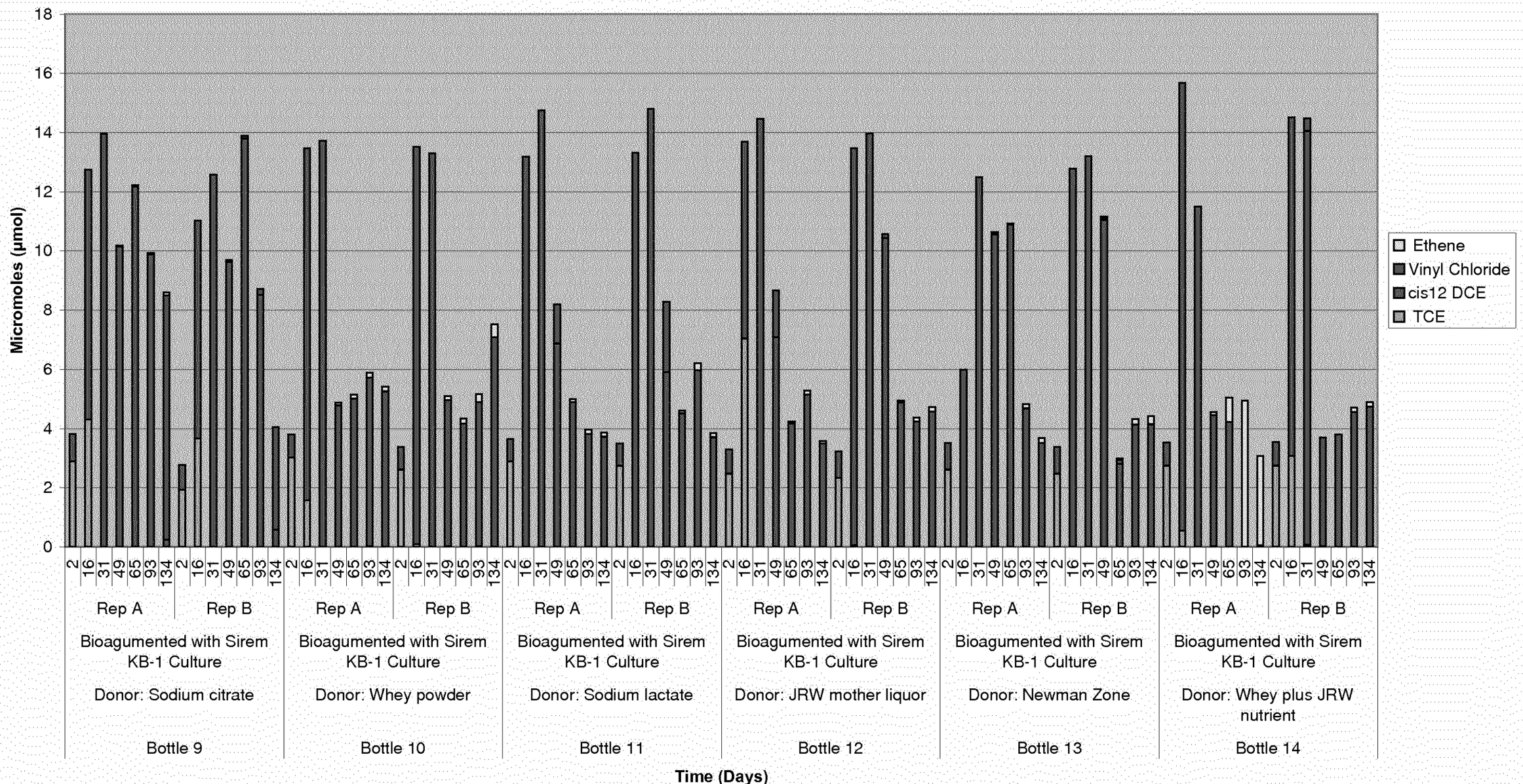

Figure 4 - TCE Degradation in Microcosms with Shaw SDC-9 Bioaugmentation Culture

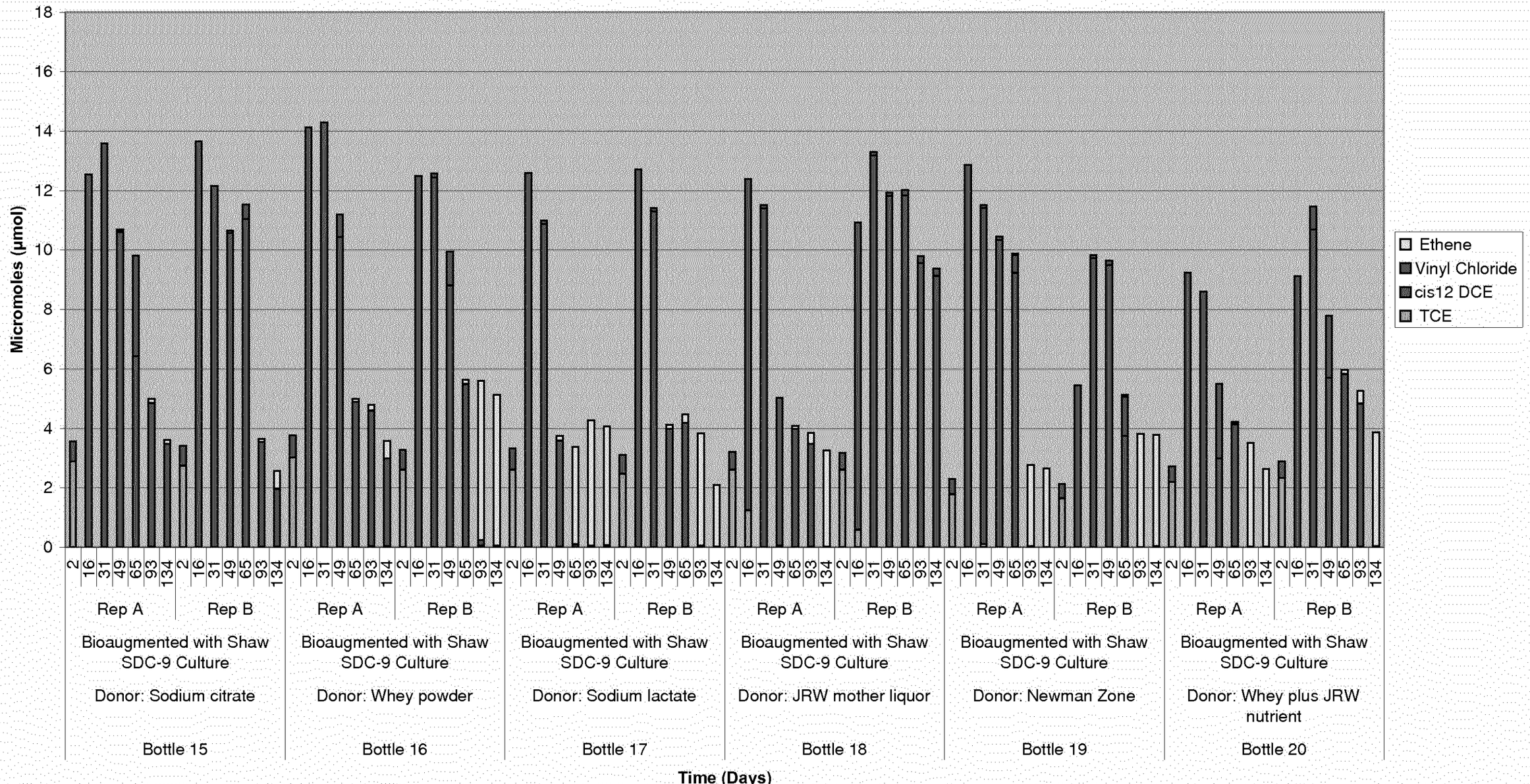

Figure 5 - COD - Control Microcosms

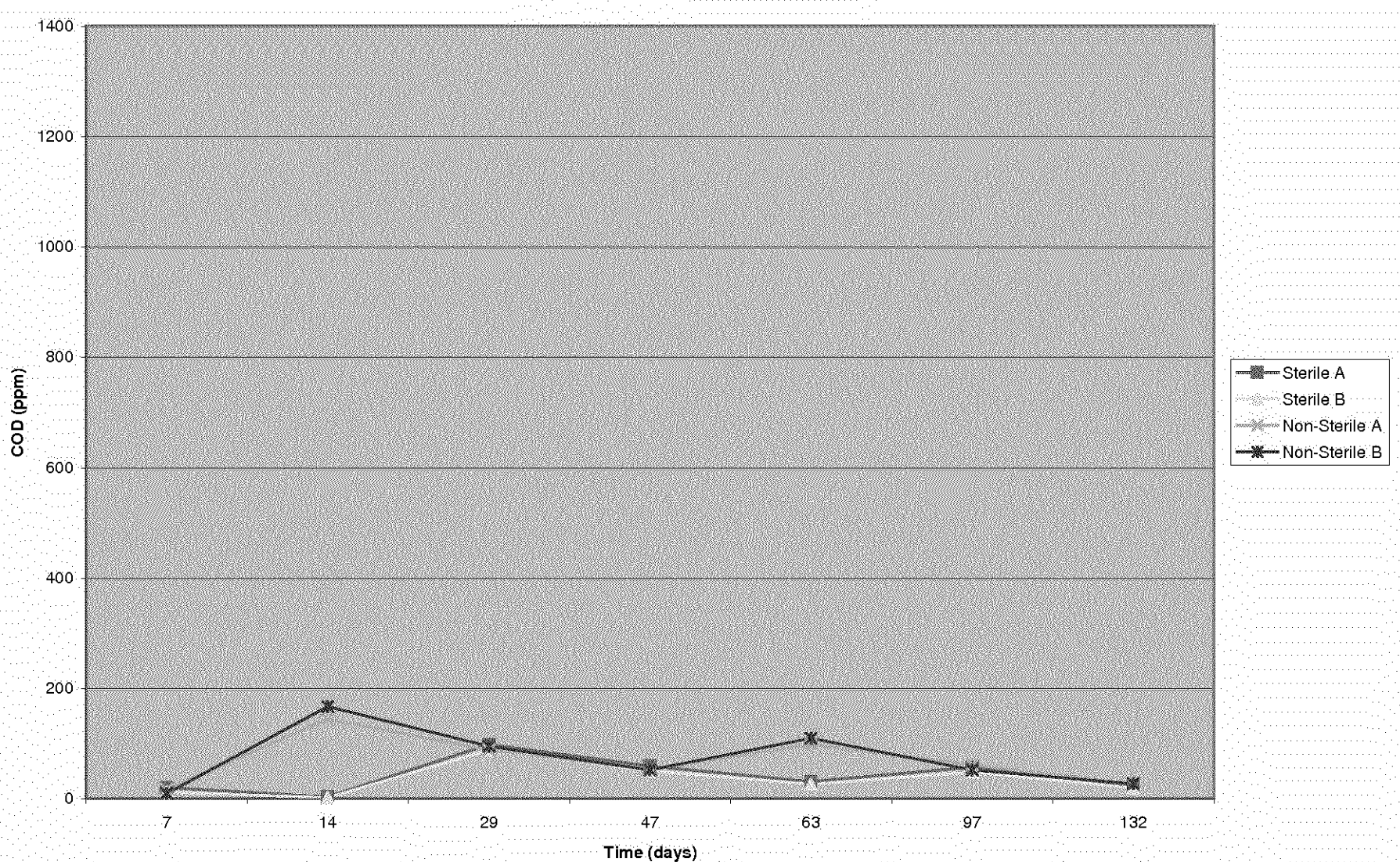

Figure 6 - COD - Microcosms with no Bioaugmentation

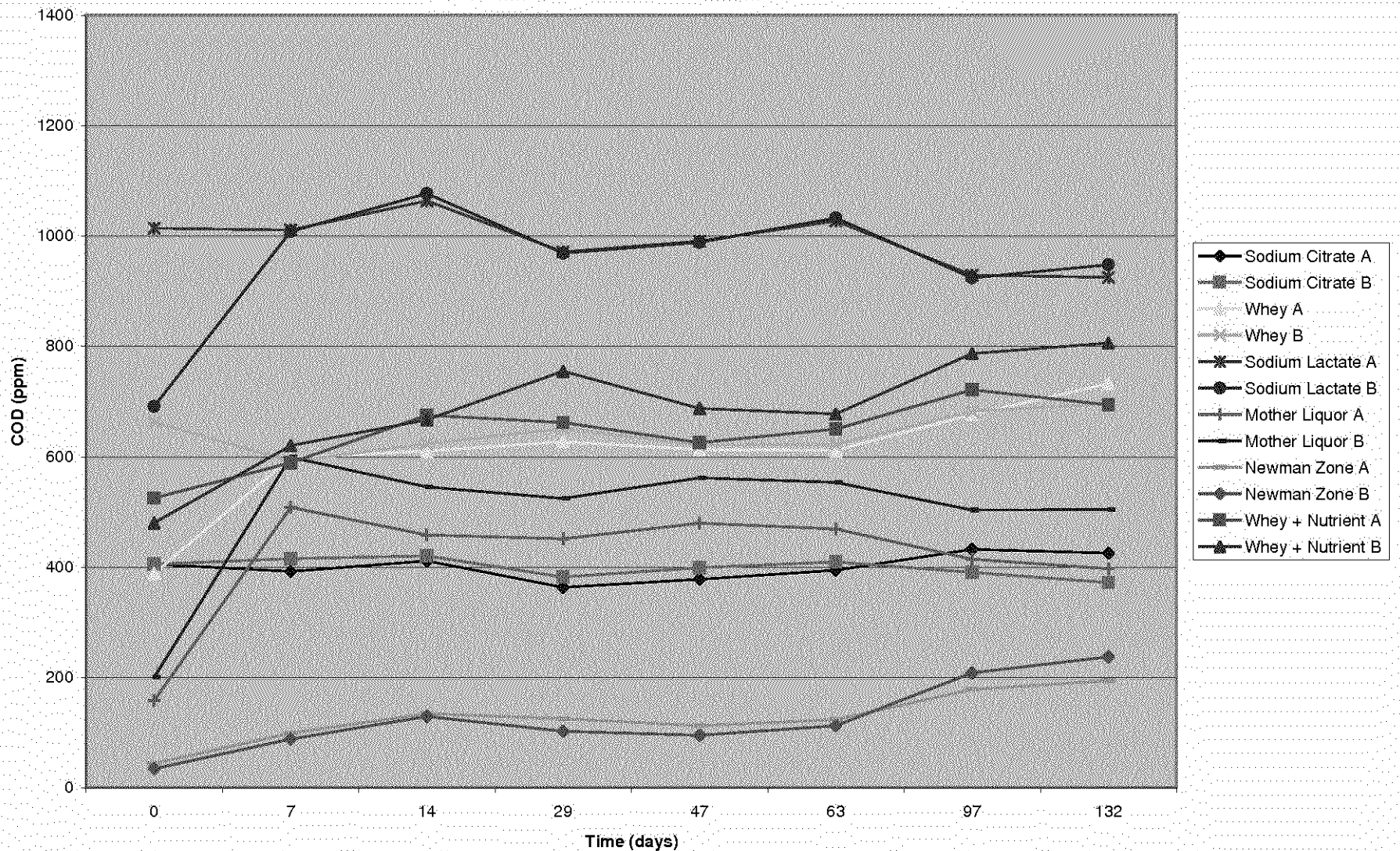

Figure 7 - COD - Microcosms with Sirem KB-1 Bioaugmentation Culture

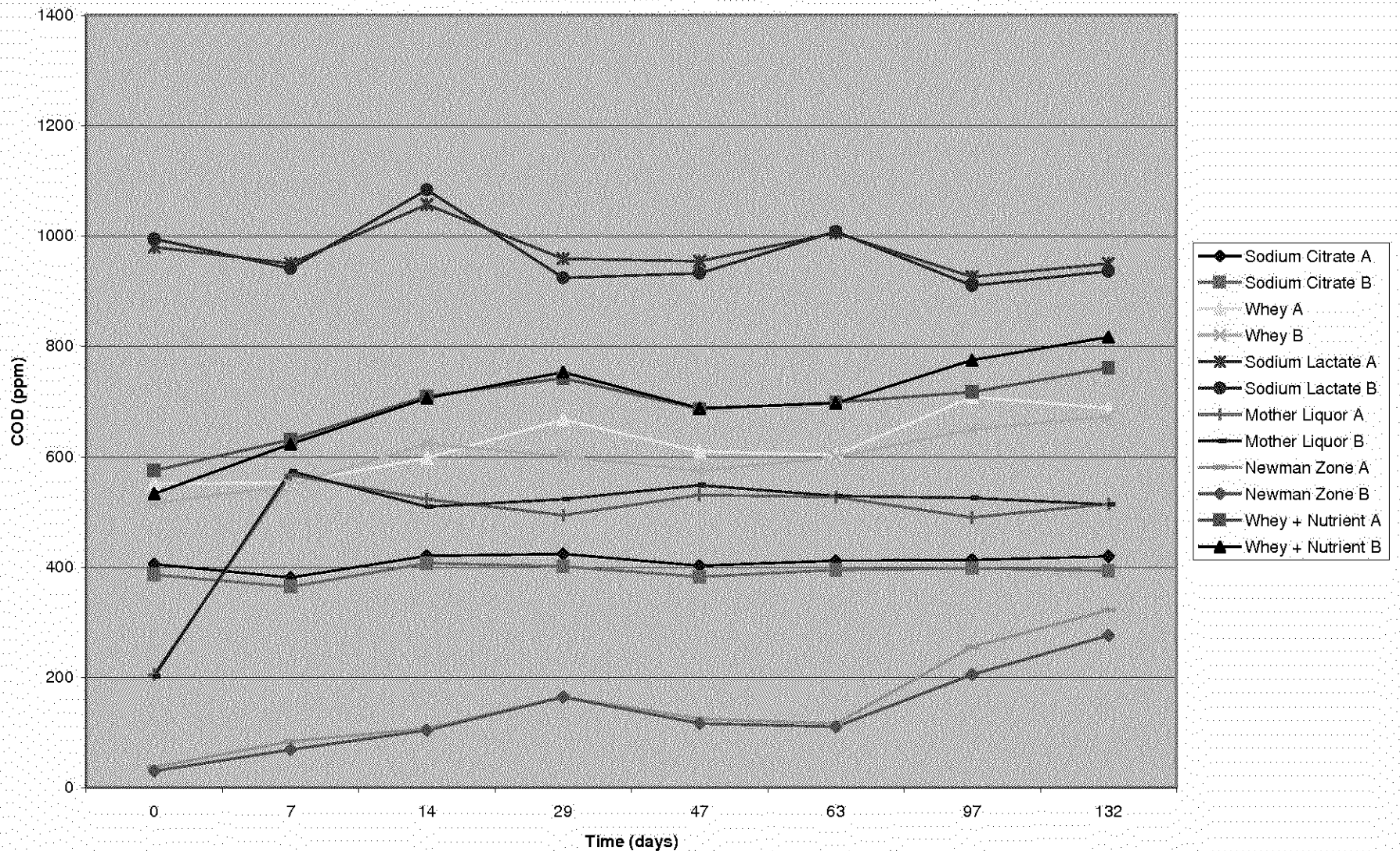

Figure 8 - COD - Microcosms with Shaw SDC-9 Bioaugmentation Culture

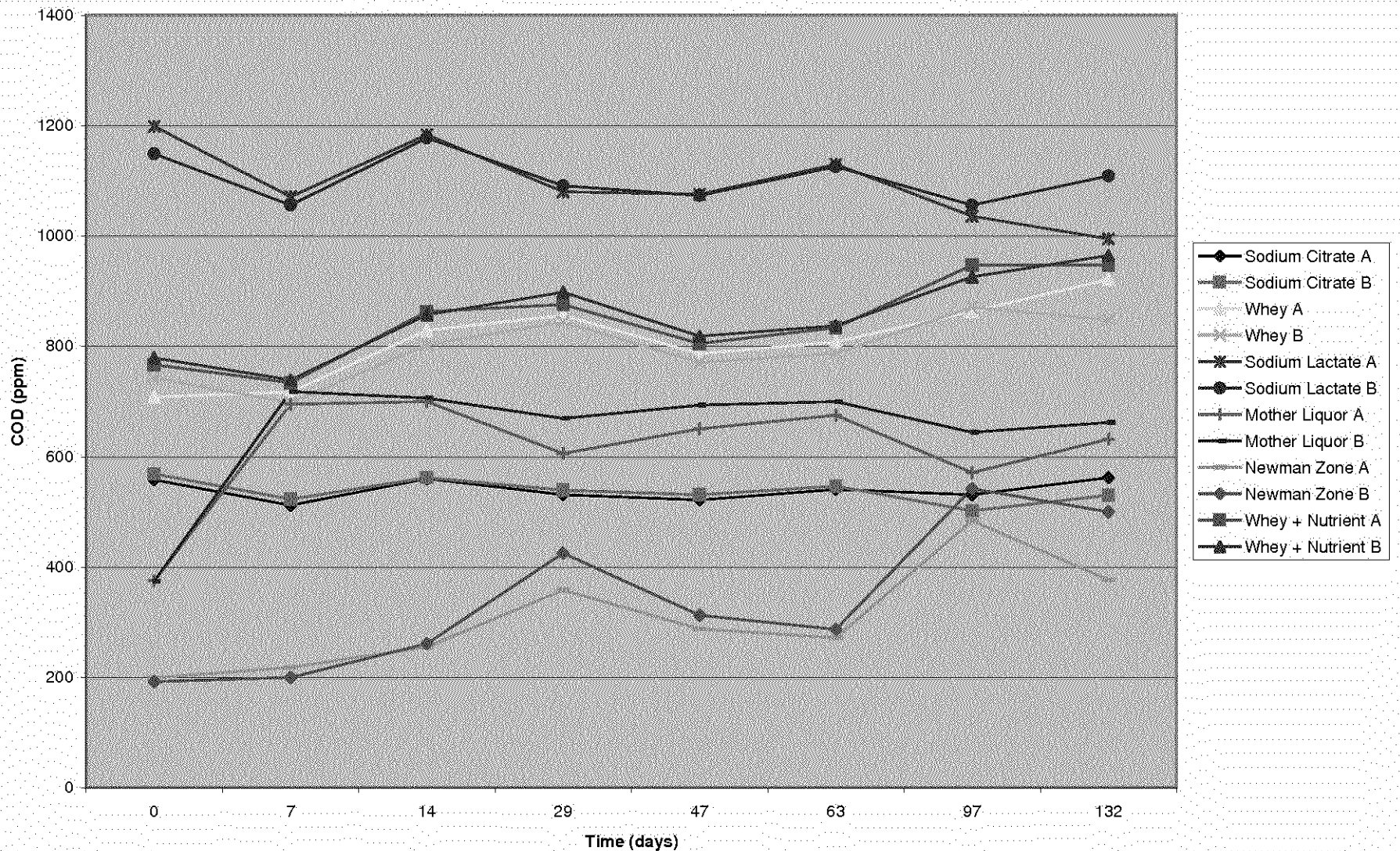

Figure 9 - Headspace Gas Production in Control Micorocosms

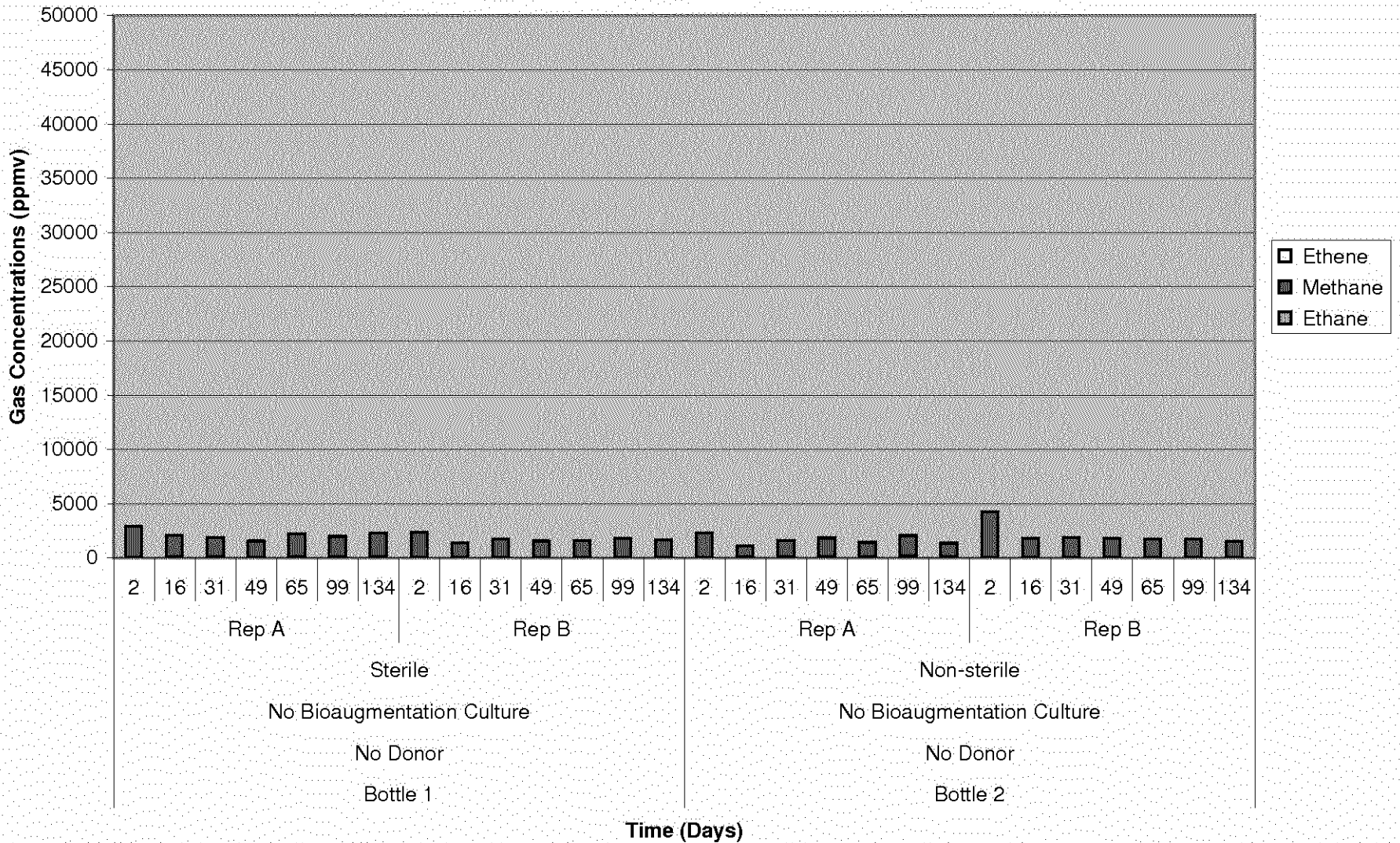

Figure 10 - Headspace Gas Production in Microcosms with No Bioaugmentation

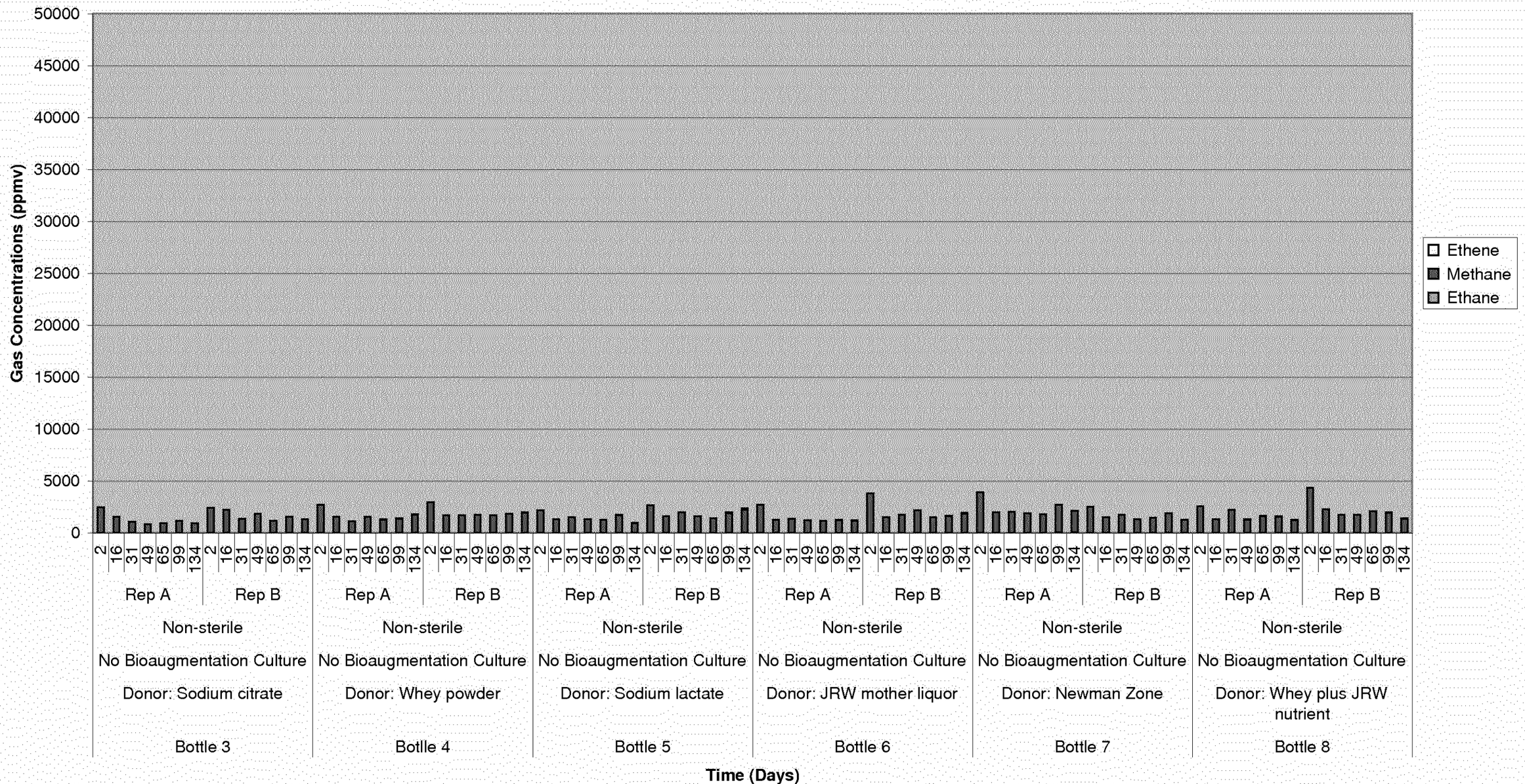

Figure 11 - Headspace Gas Production in Microcosms Bioaugmented with Sirem KB-1 Culture

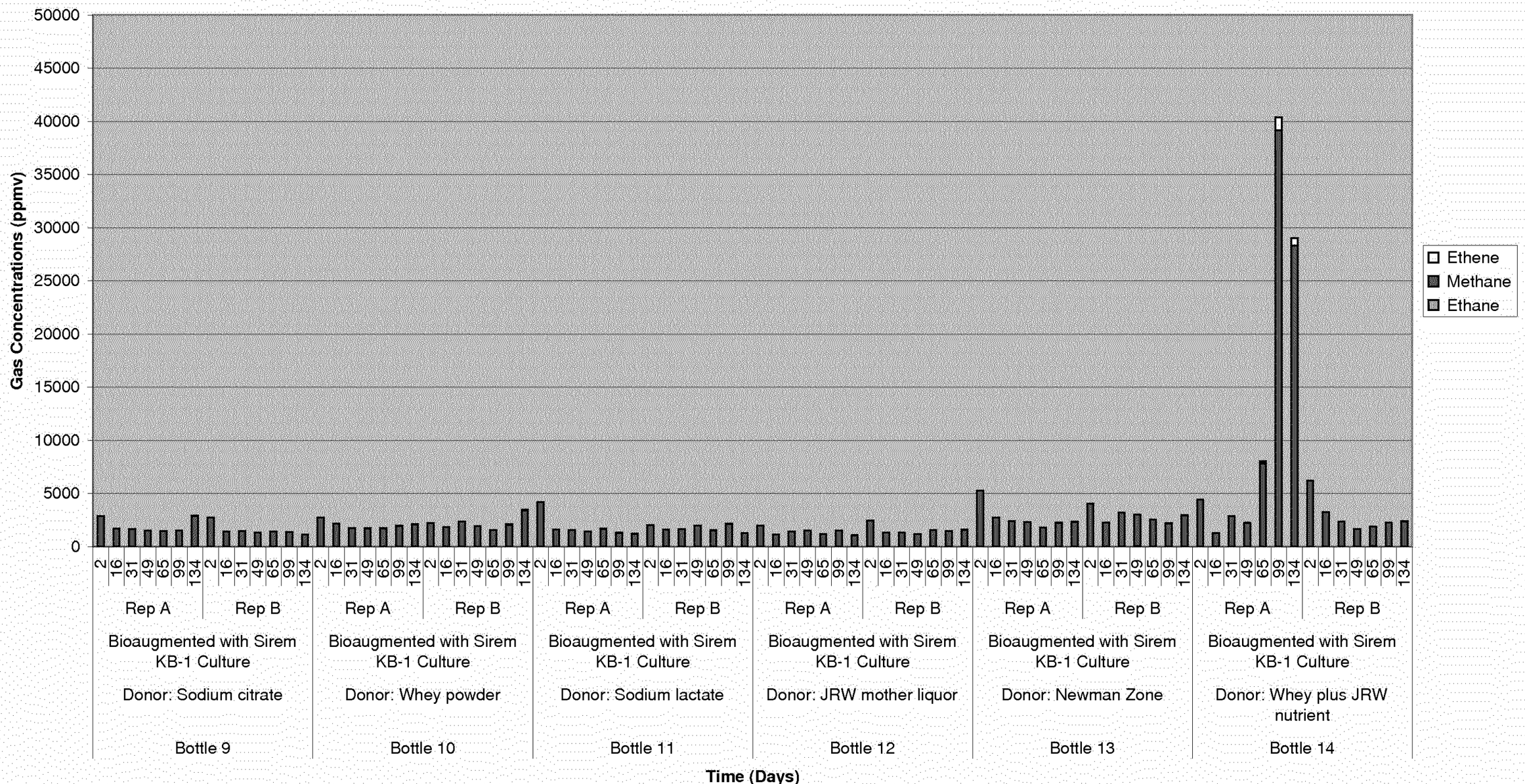

Figure 12 - Headspace Gas Production in Microcosms Bioaugmented with Shaw SDC-9 Culture

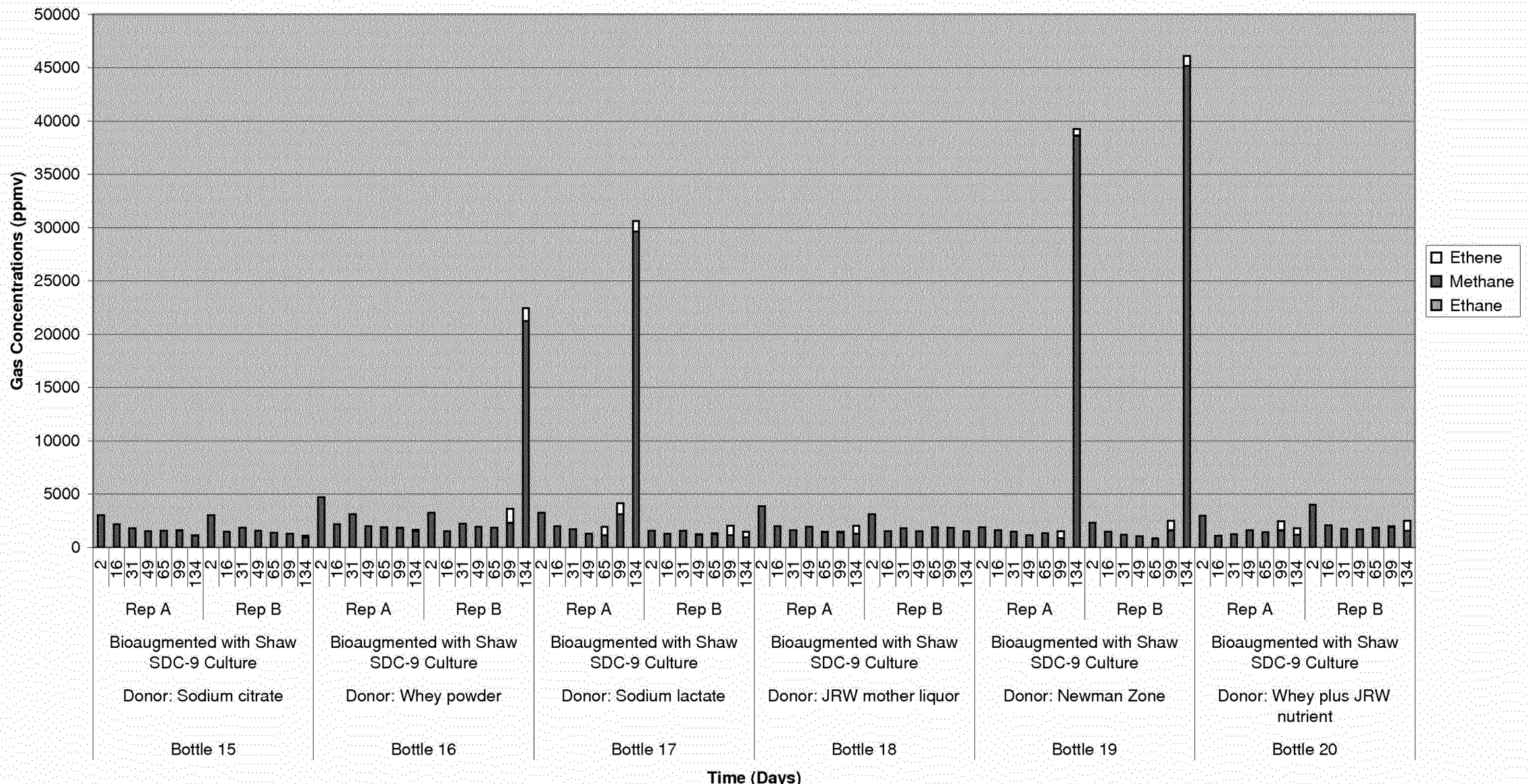

Figure 1A - pH - Control Microcosms

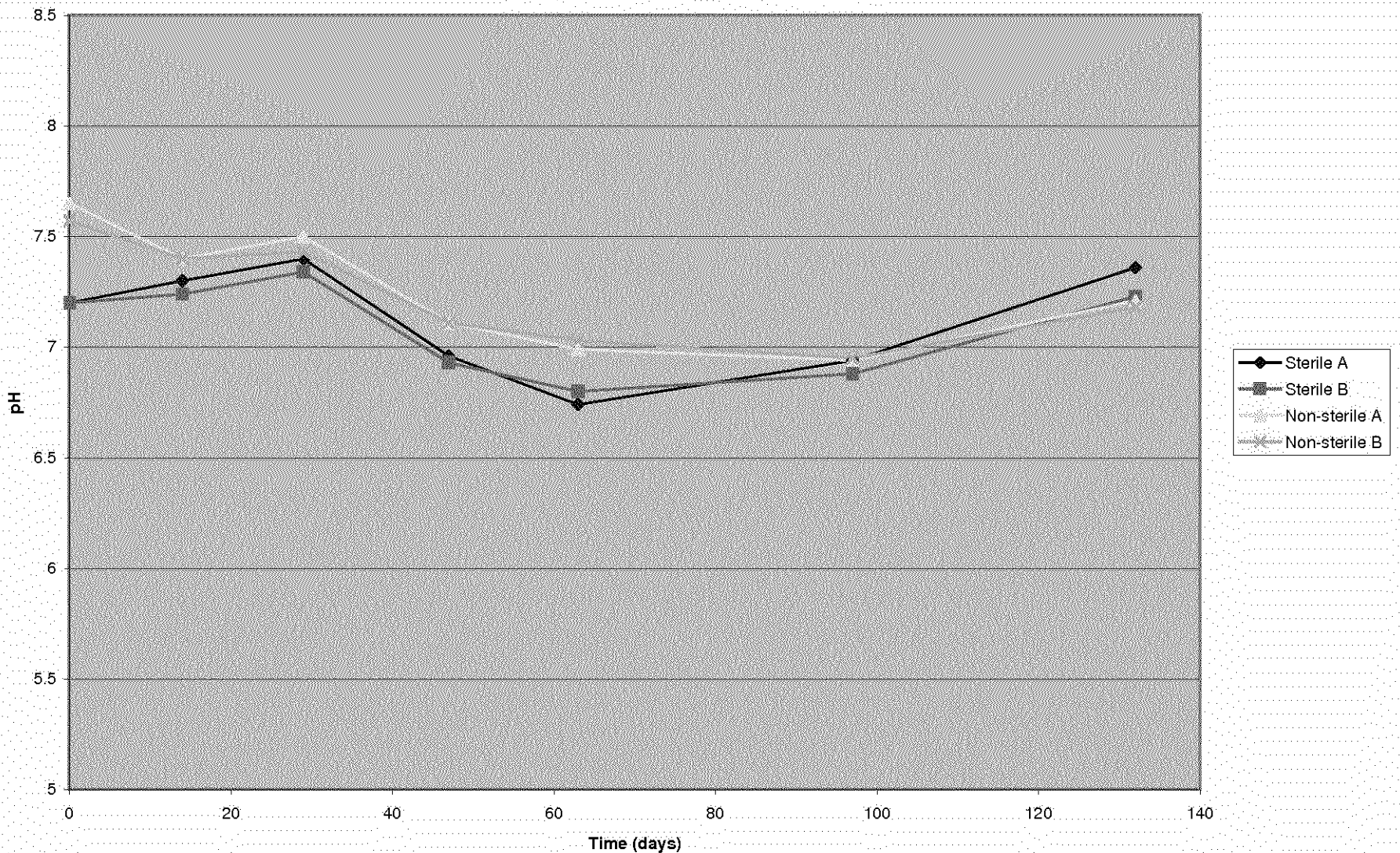

Figure 2A - pH - Microcosms with no Bioaugmentation

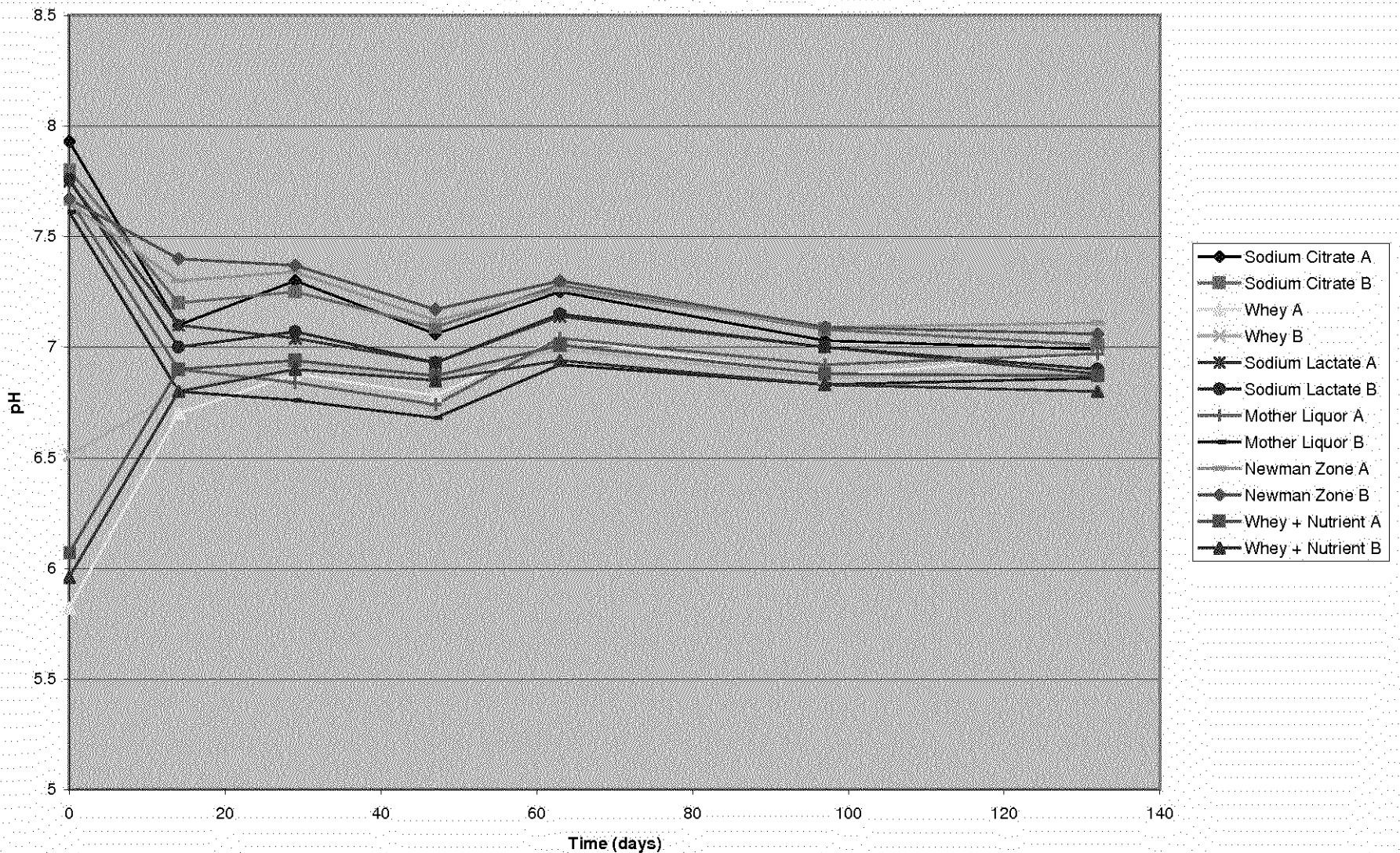

Figure 3A - pH - Microcosms with Sirem KB-1 Bioaugmentation Culture

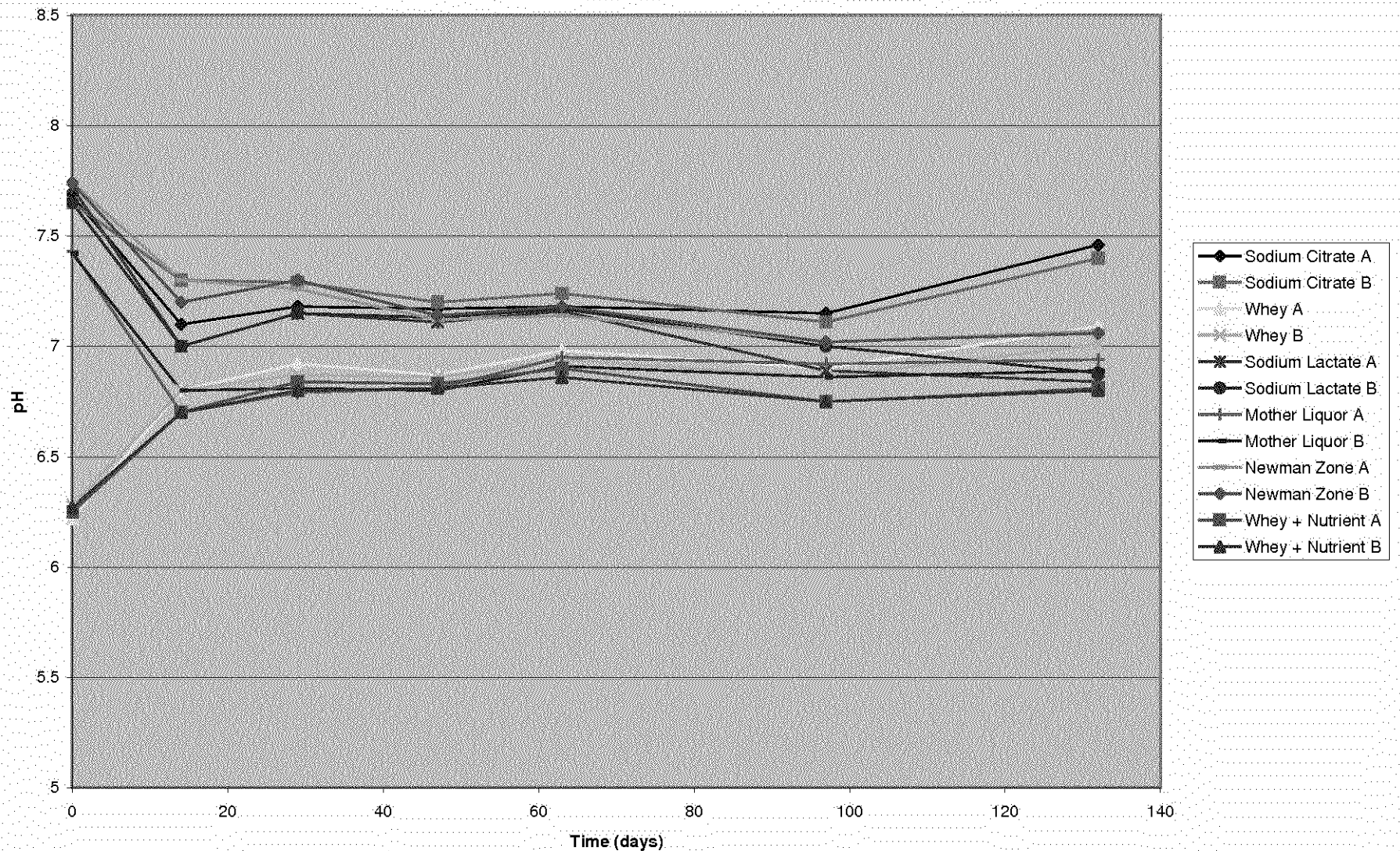

Figure 4A - pH - Microcosms with Shaw SDC-9 Bioaugmentation Culture

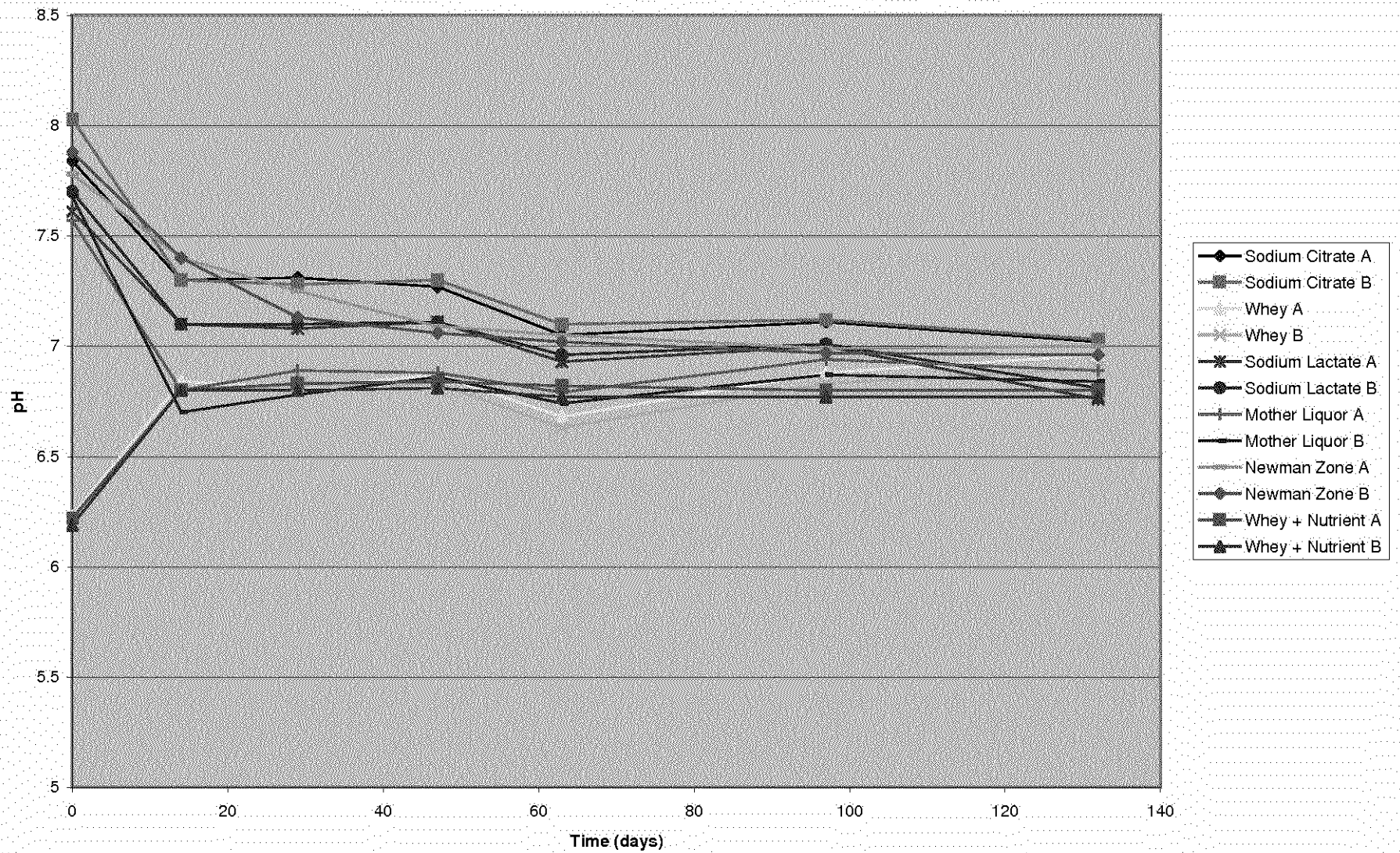

Figure 5A - SO4 - Control Microcosms

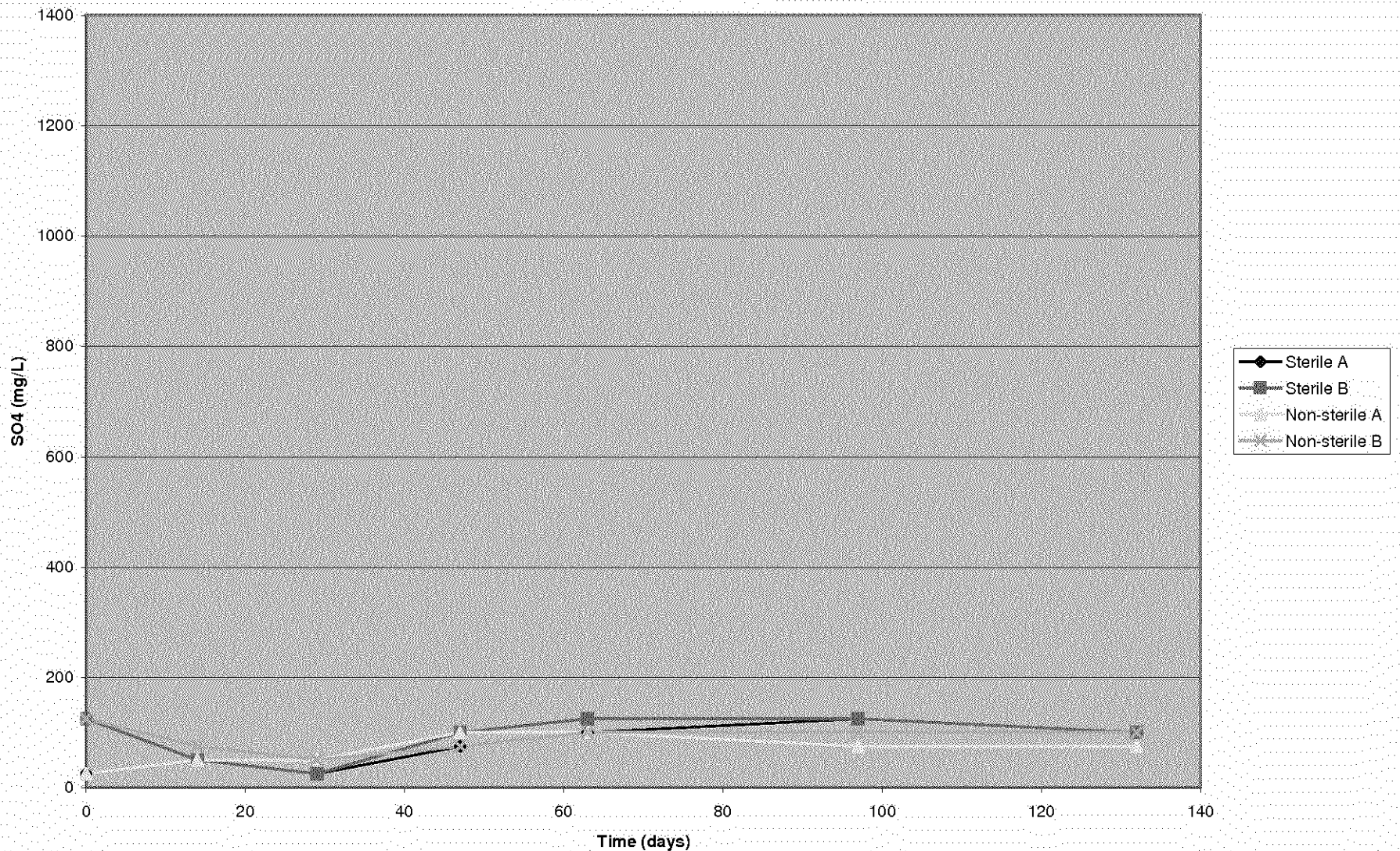

Figure 6A - SO4 - Microcosms with no Bioaugmentation

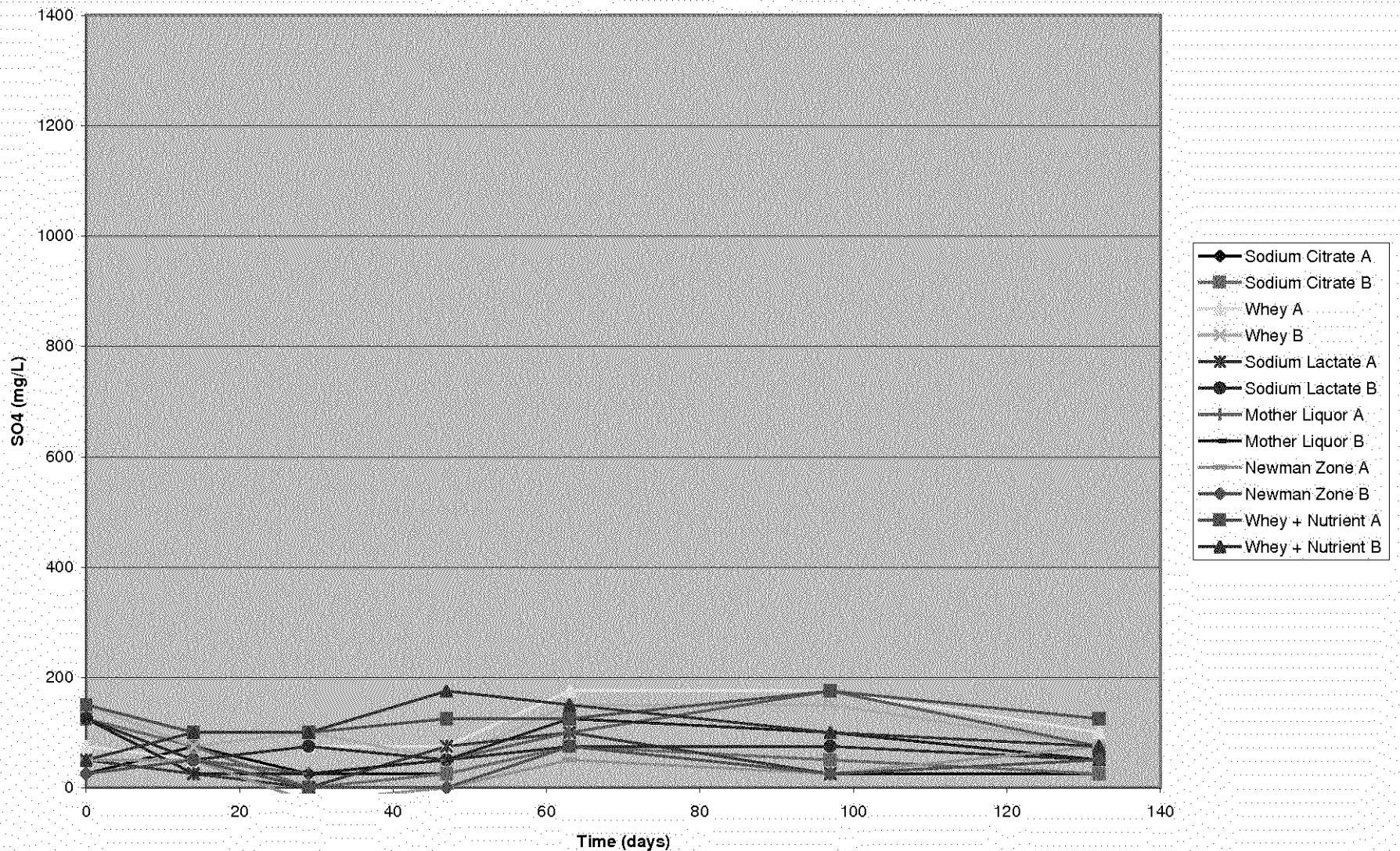

Figure 7A - SO4 - Microcosms with Sirem KB-1 Bioaugmentation Culture

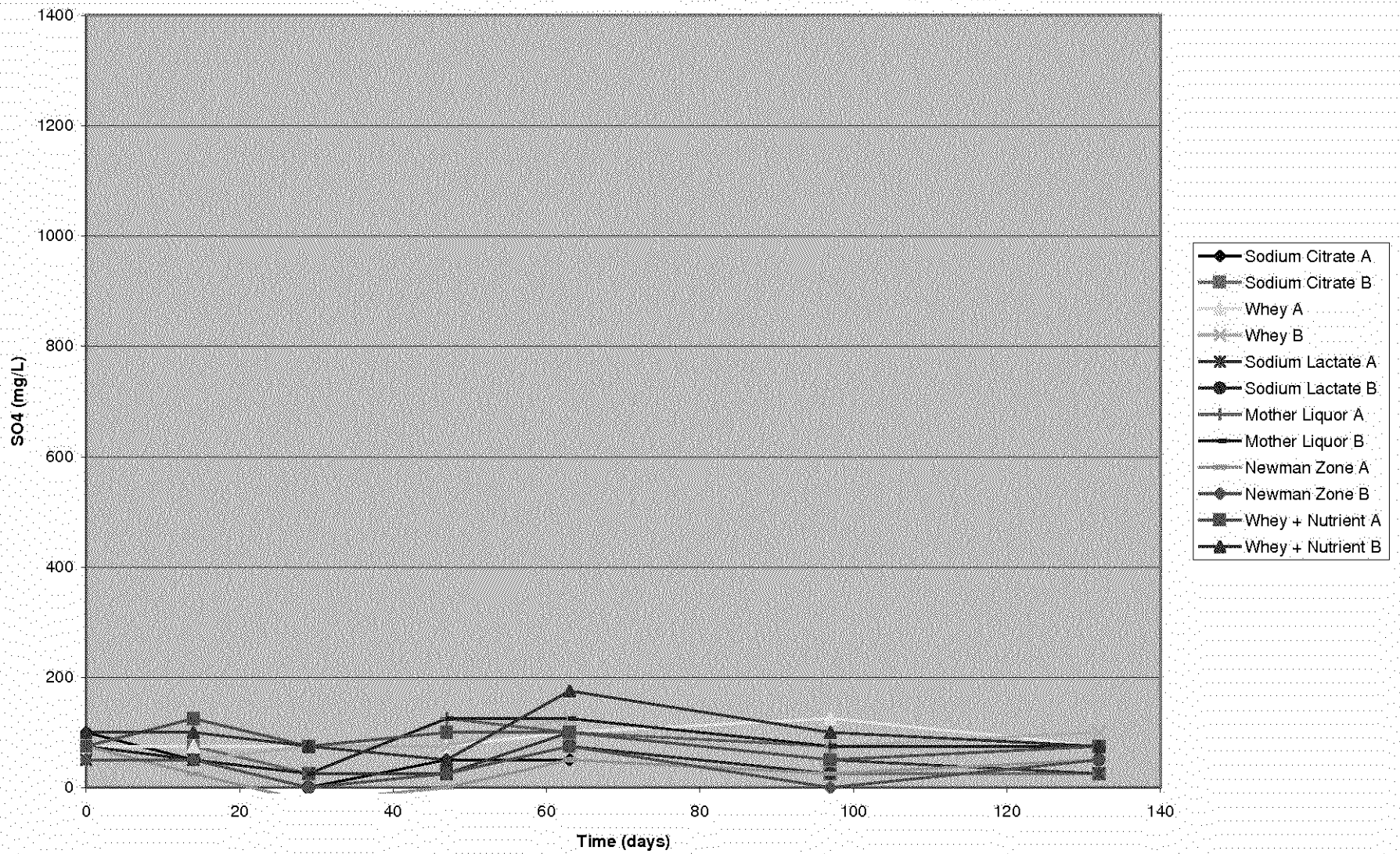
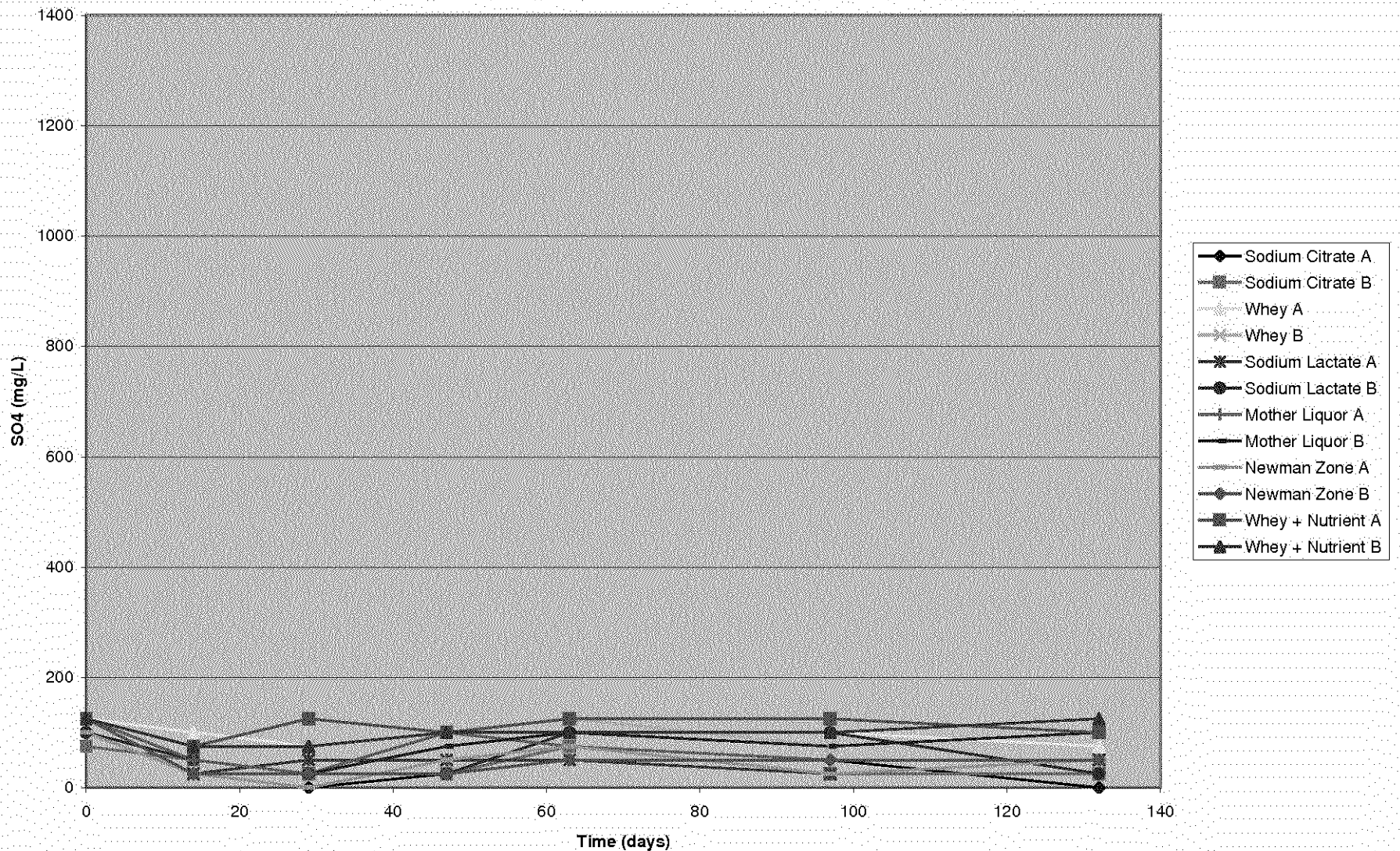
Figure 8A - SO4 - Microcosms with Shaw SDC-9 Bioaugmentation Culture