OPTIMIZATION OF BIOLOGICAL NITROGEN REMOVAL FROM FERMENTED DAIRY MANURE USING LOW LEVELS OF DISSOLVED OXYGEN

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
In partial fulfillment of the requirements for the degree of

Master of Science
In Environmental Engineering

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October 22, 2007
Blacksburg, Virginia

Keywords: nitritation, nitrification, N removal, denitrification, dairy manure treatment, simultaneous nitrification denitrification, nitrification inhibition, fermented dairy manure, NGR, dairy manure, inhibition mechanisms

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ABSTRACT

A pilot scale nitrogen (N) removal system was constructed and operated for approximately 365 days and was designed to remove inorganic total ammonia nitrogen (TAN) from solids-separated dairy manure. An anaerobic fermenter, upstream of the N removal reactor, produced volatile fatty acids (VFAs), to be used as an electron donor to fuel denitrification, and TAN at a COD:N ratio of 18:1. However, sufficient amounts of non-VFA COD was produced by the fermenter to fuel the denitrification reaction at an average NO_3^- removal rate of 5.3 ± 2 mg/L NO_3^--N. Total ammonia N was removed from the fermenter effluent in an N removal reactor where a series of aerobic and anoxic zones facilitated aerobic TAN oxidation and anoxic NO_3^- and NO_2^- reduction. The minimum dissolved oxygen (DO) concentration allowing for complete TAN removal was found to be 0.8 mg/L. However, TAN removal rates were less than predicted using default nitrifying kinetic parameters in BioWin®, a biological modeling simulator, which indicated the presence of a nitrification inhibitor in fermented dairy manure. Furthermore, an N balance during the aerobic zone indicated that simultaneous nitrification-denitrification (SND) was occurring in the aerobic zone of the N removal reactor and was most apparent at DO concentrations below 1.3 mg/L.

A series of nitrite generation rate (NGR) experiments confirmed the presence of an inhibitor in fermented dairy manure. A model sensitivity analysis determined that the most sensitive ammonia oxidizing bacteria (AOB) kinetic parameters were the maximum specific growth rate, $\hat{\mu}_{AOB}$, and the substrate half saturation coefficient, $K_{NH_4^+}$. Nitrifying inhibition terms of competitive, non-competitive, mixed competitive, and un-competitive were applied to the growth rate equation in BioWin® but an accurate representation of the observed TAN removal rates in the pilot scale system could not be found by adjusting the $\hat{\mu}_{AOB}$ and $K_{NH_4^+}$ alone. Reducing the default BioWin® hydrolysis rate by approximately 50% produced a more accurate calibration for all inhibition terms tested indicating that the hydrolyization of organic N in dairy manure is less than typical municipal waste water.

ACKNOWLEDGMENT

People

I would like to thank and acknowledge the following people for their support and assistance during this project: My advisor Dr. Nancy Love, Professor of Civil and Environmental Engineering, for her guidance and encouragement during my work. My peer advisor, Kevin Gilmore, for his guidance with the project direction and objectives as well as his assistance in the laboratory. Dr. Jactone Arogo Ogejo, Professor of Biological Systems Engineering and Dr. Katharine Knowlton, Professor of Dairy Science for their guidance throughout the duration of this project and their contributions as committee members. Dr. Linsey Marr for her contribution as a committee member. Imre Takacs, with EnviroSim Associates Ltd., for his help and support with the modeling efforts of this project. Julie Petruska, lab supervisor, for her help in the laboratories and analytical methods. Jody Smiley, instrumentation lab technician, for her assistance with sample analysis. Barry Musick for his help with reactor operation and sampling collection. The members of my lab group for their help with reactor operation, sample collection and analysis, and help with analytical methods. I would like to thank Dale Gardner of the Virginia State Dairyman's Association. Finally, I would like to thank my family for their support during my studies at Virginia Tech.

Organizations

Funding for this project was provided by the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET). Funding for the facility that housed this project was provided by the Virginia Agricultural Council.

Attribution

Several colleagues and coworkers aided in the writing and research behind several of the chapters of this dissertation. A brief description of their background and their contributions are included here.

Nancy G. Love - Ph.D. (Department of Civil and Environmental Engineering, Virginia Tech) is the primary Advisor and Committee Chair. Prof. Love provided research guidance, technical expertise, and professional development throughout my experience as a Master's student at Virginia Tech. Furthermore, Prof. Love provided technical assistance and guidance in the composition of Chapters 3 and 4 of this Thesis document.

Chapter 3: Optimization Of Biological Nitrogen Removal From Fermented Dairy Manure Using Low Levels Of Dissolved Oxygen

Chapter 4: Nitrification Inhibition by fermented dairy manure: Identifying the presence of an inhibitor and its effect on AOB kinetic parameters.

Nancy G. Love – See above description.

Kevin R. Gilmore – Candidate for Ph.D. (Department of Civil and Environmental Engineering, Virginia Tech) was a student in the author's group and contributed during his graduate studies to chapters 3 and 4 in terms of discussing lab practices, nitrogen removal processes and software modeling.

Katharine F. Knowlton - Ph.D. (Department of Dairy Science, Virginia Tech). Prof. Knowlton served as a committee member and contributed to the discussion of nitrogen content in dairy waste related to diet and dairy operation.

Jactone Arogo Ogejo - Ph.D. (Department of Biological Systems Engineering, Virginia Tech). Prof. Ogejo provided technical assistance related to dairy operation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LITERATURE REVIEW

1 EXECUTIVE SUMMARY

Animal feeding operations (AFOs) produce manure waste that is a valuable asset for crop fertilization due to its high nutrient content. However, when nutrients such as total ammonia nitrogen (TAN, comprised of ammonia (NH_3) plus ammonium (NH_4^+)) are applied in excess, they can leech into surrounding waterways and deteriorate the environment through a process known as eutrophication. Effective nitrogen (N) management systems that remove excess N in a cost effective and efficient way while maximizing the bioavailability of N for crop fertilization are of interest. One such technique is biological N removal through a process known as nitrification coupled with denitrification. Nitrification is accomplished by two groups of autotrophic bacteria, ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB), which oxidize NH_3 to NO_2^- and NO_2^- to NO_3^-, respectively. On the other hand, denitrification is accomplished by heterotrophic bacteria and reduces NO_2^- and/or NO_3^- to N_2 gas while consuming an external energy source under anoxic conditions. In the absence of sufficient bio-available electron donors, exogenous sources such as methanol or acetic acid are typically added to the process to fuel the denitrification step.

Biological N removal systems have been processing N in domestic sewage for decades and have been studied extensively. However, the concentrations of nutrients and organics present in dairy waste are orders of magnitude higher than those seen in domestic wastewater (WW) and may require modification to conventional configurations to remove N in the most cost effective manner. In addition, AFOs do not have access to the same resources as municipalities to treat their waste. One such technology for removing N is known as nitritation combined with denitritation where NH_3 is oxidized to NO_2^- only and then denitrified directly to N_2.

Removing N via NO_2^- as opposed to NO_3^- reduces aeration requirements by 25%, reduces carbon source requirements for denitrification by 40% and improves denitrification rates. However, the success of this strategy is dependent on reducing the growth rate of NOB compared to AOB so that the production of NO_3^- is minimized. One method for accomplishing this strategy is using low levels of dissolved oxygen (DO) where AOB are known to out-compete NOB for the available electron acceptor, O_2, as long as residual TAN is present. Therefore, the objectives of this research were to remove N from solids-separated dairy manure through a nitritation/denitritation process using low levels of DO in the aerobic zone. Additionally, the use of anaerobic fermentation of the waste itself to produce an energy source for denitrification in the form of volatile fatty acids (VFAs) was investigated.

A two step reactor system was constructed and operated for 363 days. The first reactor was a 30 L anaerobic fermenter with a solids retention time (SRT) equal to the hydraulic retention time (HRT) of two days and designed to produce VFAs. The second reactor was a 150 L N removal reactor where N removal was accomplished through a series of anoxic and aerobic phases designed to facilitate nitritation and denitritation. Each reactor operated as a sequencing batch reactor with 5 L of feed being pumped three times per day. The DO in the N removal reactor was slowly lowered in 0.1 mg/L increments beginning at 2.0 mg/L from days 220 to 363 to determine the minimum DO concentration that would allow complete TAN removal. A cross cycle analysis was performed at each DO concentration by taking samples at various time intervals during an eight hour feed cycle. These provided valuable information in assessing the reactor performance.

Nearly complete TAN removal was witnessed in the N removal reactor at DO levels between 2.0 and 0.8 mg/L. Negligible nitrifying activity was witnessed at a DO concentration of 0.7 mg/L. Therefore, the minimum DO concentration required for nitrification was found to be 0.8 mg/L. However, TAN was removed in each cross cycle at rates that were less than expected based on simulated results obtained from a biological software package called BioWin®. This suggests that either the model parameters were not correct for application to dairy waste, or a nitrification inhibitor was present in the fermenter effluent.

Nitrification inhibition experiments using nitrite generation rates as an indicator of inhibition activity were performed with various dilutions of the fermenter supernatant. Results clearly showed that an inhibitor was present in the fermented dairy manure. Consequently, the competitive, non-competitive, un-competitive and mixed competitive inhibition models were evaluated using sensitivity analysis based on best fit to the data by adjusting both AOB maximum specific growth rate ($\hat{\mu}_{AOB}$) and AOB substrate half saturation coefficient (K_{S,NH_3}). Model calibration suggests that the inhibitor may act in a non-competitive manner, but insufficient data were collected to elucidate the inhibition mechanism conclusively.

Soluble COD measurements taken during each cross cycle suggested that the electron donor produced by the fermenter was consumed in the aerobic zone before all TAN was oxidized and was therefore not available as an energy source for denitrification. Although denitrification rates measured during the cross cycles were four times slower when compared with denitification tests performed with acetate alone, NO_3^- was still denitrified during the final anoxic zone. This demonstrates that the system was not entirely carbon source limited but used slowly biodegradable COD instead of the VFAs.

Observations of N removal show that SCOD may have also been used by heterotrophic denitrifying bacteria during the aerobic zone through a process known as simultaneous nitrification-denitrification (SND). A reasonable N balance incorporating all measured N species as well as estimates of N used for biomass growth suggested that simultaneous nitrification-denitrification (SND) was occurring in the reactor and was most apparent at DO levels between 1.3 and 0.8 mg/L. This is important because the TAN and VFAs in the fermenter supernatant could be used simultaneously in the N removal reactor to achieve N removal.

Findings from this research show that AFOs can reduce aeration costs associated with excess manure N removal by maintaining a low DO concentration during the aerobic phase. Additionally, sufficient COD was found in unfermented dairy manure to support full denitrification. While the denitrification rates were improved when using readily biodegradable energy sources, dairies often use anaerobic stabilization in lagoons that have relatively large SRT values where any NO_2^- or NO_3^- produced from the N removal reactor could be denitrified. Therefore, the addition of a fermentation reactor, or external energy source is not required for a N removal system using dairy waste. Soluble COD in dairy manure also allowed for SND to occur in the N removal reactor and was most apparent at DO levels below 1.3 mg/L. Using SND as a strategy minimizes the accumulation of NO_2^- and NO_3^- in the aerobic zone and reduces the time required for denitrification.

Additionally, biological modeling software packages can be used to aid in the design of such systems, but an unknown inhibitor found in the dairy waste tested requires further calibration of the default parameters. Specifically, the AOB kinetic parameters, $\hat{\mu}_{AOB}$ and K_{S,NH_3}, and the mechanism of the inhibitor needs to be defined with the waste and mixed liquor used in the treatment system.

2 LITERATURE REVIEW

2.1 Dairy Waste Characterization and Management

Dairy waste characteristics vary greatly depending on season (due primarily to temperature effects), operation size, collection and treatment method, and other constituents that might be added to the waste stream. Dairy cows typically reside in a facility that allows the cows to eat and sleep in a dry area that contains some type of bedding. Nearly all of the bedding will be pushed or kicked and added to the manure (USDA, 1992). Additionally, milking parlor wastewater and washing water is added to the manure before treatment. Dairies typically use scraping or flushing systems to remove manure from the animal feeding facilities (Van Horn et al., 1994). Additionally, dairies often use mechanical separation to remove solids from their waste treatment process which produces two waste streams (solid and liquid) that both contain high concentrations of nutrients and organics (Van Horn et al., 1994) that are orders of magnitude larger than those found in municipal wastewater (Table 2-1). Specifically, an important value for N removal systems, total COD:TAN ratio, measured in dairy liquid separator effluent is 2.6 times higher than the same ratio measured in typical municipal wastewater. The high solids concentrations require unique design strategies for treating dairy wastewater. Furthermore, high COD concentrations cause high oxygen demands when treating dairy manure aerobically. Consequently, fully aerobic treatment is not used to treat dairy manure.

Table 2-1: Dairy manure and municipal wastewater characteristics.

Constituent	Dairy liquid separator effluent[1]	Municipal[2]
TAN – N (mg/L)	840	25
TKN (mg/L)	3,080	40
Total P (mg/L)	300	7
Total COD (mg/L)	37,500	430
Total COD:TKN	12.2	10.8
Total COD:TAN	45	17
Soluble COD (mg/L)	15,378	--
TSS / VSS (mg/L)	32,080 / 28,330	210 / 160

[1](Knowlton et al., 2005)
[2]Values for medium strength municipal wastewater (Tchobanoglous et al., 2003)

Excess nutrients such as N can be detrimental to water bodies and their surrounding environments because they cause eutrophication. Agriculture, including animal feeding operations (AFOs), contributes 38 percent of the total N load into the Chesapeake Bay, located on the east coast of the United States, as compared to 20 percent contributed by all point sources (Herbst, 2002). Due to its relatively low cost, biological N removal is the best option for AFOs to manage excess manure N that is eventually land applied and threatens the water quality of nearby water bodies.

2.2 Nitrogen and Biological Nitrogen Removal (BNR)

2.2.1 Conventional Biological Nitrogen Removal

Nitrogen in dairy waste primarily exists in the reduced form as organic N or inorganic N as TAN (Knowlton et al., 2005). Conventional biological nutrient removal (BNR) systems remove reduced inorganic N in domestic wastewater treatment applications and might be applicable to treating dairy manure with excess N. The first step in conventional BNR is accomplished by two distinct groups of bacteria, ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB). AOB convert TAN to NO_2^- with hydroxylamine (NH_2OH) as an intermediate. NOB then convert NO_2^- to nitrate (NO_3^-) (Equations 2-1 and 2-2). Finally, NO_3^- is converted to N gas (N_2) with, nitrite (NO_2^-), nitric oxide (NO), and nitrous oxide (N_2O) as intermediary compounds (denitrification) by heterotrophic bacteria under anoxic conditions while consuming an external energy source (electron donor, acetic acid assumed here) (Equations 2-3 and 2-

4). Conventional BNR systems applied to treat sewage often require the addition of an electron donor such as methanol to achieve full denitrification (Grady et al., 1999).

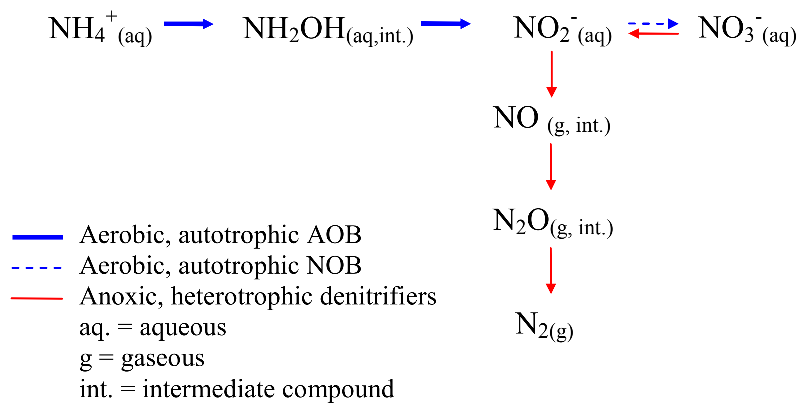

Figure 2-1: Biological N removal.

NH_4^+ oxidation (AOB):	$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + 2H_2O$	Equation 2-1
NO_2^- Oxidation (NOBs):	$NO_2^- + 0.5O_2 \rightarrow NO_3^-$	Equation 2-2
Denitrification via NO_3^-:	$5C_2H_4O_2 + 8NO_3^- + 8H^+ \rightarrow$	Equation 2-3[a]
	$4N_2 + 10CO_2 + 14H_2O$	
Denitrification via NO_2^-:	$3C_2H_4O_2 + 8NO_2^- + 8H^+ \rightarrow$	Equation 2-4[a]
	$4N_2 + 6CO_2 + 10H_2O$	

[a]Equations 2-3 and 2-4 assume acetic acid CH_3COOH is the electron donor

In contrast to domestic wastewater treatment, dairy manure contains high concentrations of reduced N and organics, and may benefit from the use of novel, cost effective N removal techniques. Several techniques have been developed over the past decades that utilize conventional and newly discovered metabolisms, such as anaerobic ammonia oxidation (anammox), to achieve N removal in a more efficient way. These methods include: single reactor system for high ammonia removal over nitrite (SHARON) (van Kempen et al., 2001), completely autotrophic nitrogen removal over nitrite (CANON) (Sliekers et al., 2002), oxygen-limited autotrophic nitrification-denitrification (OLAND) (Kuai and Verstraete, 1998), and N removal via NO_2^- (nitritation/denitritation) (Ruiz et al., 2003).

2.2.2 SHARON

The SHARON process removes N via the NO_2^- pathway. It operates with no sludge retention such that the hydraulic retention time (HRT) and the solids retention time (SRT) are equal. In order to process N via NO_2^-, NOBs must be inhibited such that NO_2^- is not oxidized to NO_3^-. AOBs are known to grow faster than NOBs at relatively high temperatures (Mulder et al., 2001; Yoo et al., 1999), low sludge ages (Bock et al., 1986), high pH values (Cecen, 1996), and low levels of dissolved oxygen (Picioreanu et al., 1997; Turk and Mavinic, 1989) The SHARON process utilizes these bacterial characteristics and operates under high temperatures (35^{o}C) (Mulder et al., 2001), a sludge age ranging from 1 to 2.5 days (van Kempen et al., 2001), and low levels of dissolved oxygen. The SHARON process performs best under high N:COD ratios and is typically used for treating reject water from sludge dewatering processes (van Kempen et al., 2001). As solids-separated dairy manure COD:N ratios are higher than sewage (Knowlton et al., 2005), this process might be applicable for removing excess N from dairy manure. However, DO and temperature control would have to be applied, both adding economic cost to the system.

2.2.3 Anaerobic Ammonia Oxidation (anammox)

The bacteria responsible for the anammox process use TAN as the electron donor and NO_2^- as the electron acceptor to oxidize TAN to dinitrogen gas (N_2) under anaerobic conditions. This autotrophic metabolism occurs according to the following stoichiometric relationship (vandeGraaf et al., 1997) (Equation 2-5):

$$NH_4^+ + 1.31NO_2^- + 0.0425CO_2 \rightarrow 1.045N_2 + 0.22NO_3^- + 1.87H_2O + 0.09OH^- + 0.0425CH_2O \quad \text{Equation 2-5}$$

Anammox performs best with wastewaters that have a high N:COD ratio. Low N:COD ratios allow heterotrophic denitrifiers to compete with anammox bacteria for available NO_2^--N, thereby decreasing system efficiency. Anammox bacteria grow very slowly, with a doubling time and growth rate of around 11 days and 0.003 day^{-1}, respectively (Jetten et al., 1998). These are much lower than conventional ammonia oxidizing bacteria under aerobic conditions where the doubling time and growth rate are 0.73 days and 0.04 day^{-1}, respectively (Jetten et al., 2001). These relatively slow kinetic values require long start-up times as well as effective sludge retention to ensure the success of a full scale anammox system. Nevertheless, anammox has several operational advantages over conventional BNR systems such as no external energy requirement for denitrification, low sludge production, and no oxygen demand (Jetten et al., 1998). Both the CANON and OLAND processes (discussed below) are examples of systems that use anammox.

2.2.4 *CANON*

The completely autotrophic nitrogen removal over nitrite (CANON) process is accomplished by two groups of bacteria. CANON removes N from wastewaters containing high concentrations of inorganic N and low concentrations of readily biodegradable COD. The process depends on the coexistence of Nitrosomonas-like aerobic ammonia oxidizing bacteria and Planctomycete-like anaerobic ammonium oxidizing bacteria (Third et al., 2001). Under oxygen limited conditions, TAN is oxidized to NO_2^- (Equation 2-1). NO_2^- and NH_4^+ are then simultaneously used as the electron acceptor and donor, respectively, to oxidize NH_4^+ to N_2 (Equation 2-5). The CANON process can be an effective strategy for treating wastewaters with a high N:COD ratio. While N removal rates of up to 1.5 kg N/m^3 day^{-1} have been observed in the laboratory (Sliekers et al., 2003), full scale application of the CANON process has been minimal (Ahn and Choi, 2006). Furthermore, it has not been demonstrated on dairy waste.

2.2.5 OLAND

Oxygen-limited autotrophic nitrification over denitrification (OLAND) is a similar process to CANON, where TAN is converted to N_2 with NO_2^- as an intermediary compound. However, where CANON is designed to utilize the anammox metabolism, OLAND was first termed for the process whereby both anammox and denitrification by AOB (TAN oxidation to N_2O (Bock et al., 1995)) are responsible for the production of gaseous N products and consequently, N removal (Kuai and Verstraete, 1998). Similar to CANON, the use of the OLAND process has not been demonstrated on dairy waste.

2.2.6 Nitritation/Denitritation

SHARON, anammox, CANON, and OLAND are examples of technologies that oxidize inorganic TAN in a cost effective and efficient way. However, researchers have had start-up difficulties with ANAMMOX and CANON strategies because of the low growth rates associated with the bacteria (Ahn and Choi, 2006). Of the three, SHARON has been the most effective at full-scale but requires residual effluent TAN and high temperatures to inhibit the growth of NOB (Hellinga et al., 1998; van Kempen et al., 2001). A technique known as known as partial nitrification to NO_2^- (nitritation) coupled with denitrification from NO_2^- (denitritation) has been developed over the past several decades that uses the conventional metabolisms described in section 2.2.1 in a more effective way than conventional nitrification/denitrification via NO_3^-. Removing N through the NO_2^- pathway has several advantages compared to N removal via NO_3^- including:

- 25% lower oxygen demand (van Kempen et al., 2001).
- 40% reduction in electron donor requirement for denitrification via NO_2^- (Ruiz et al., 2006)
- Denitrification rates from NO_2^- are higher than from NO_3^-. The magnitude of difference between the rates varies greatly depending on the energy source used for heterotrophic denitrification (van Rijn et al., 1996).

The success of nitritation requires the growth of NOB to be limited such that NO_2^- is not oxidized to NO_3^-. Currently, researchers have developed several different methods for limiting the growth of NOB. These include: controlling reactor temperature, applying unique aeration patterns, controlling pH (as it relates to inhibiting compounds), adding chemical inhibitors, controlling dissolved oxygen (DO) concentration, and controlling sludge age. Each of these strategies will be discussed next.

Reactor Temperature. AOBs are known to have higher growth rates than NOBs at temperatures that are above normal operating temperatures of domestic wastewater treatment plants (WWTP) (Hellinga et al., 1998) (
Figure **2-2**).

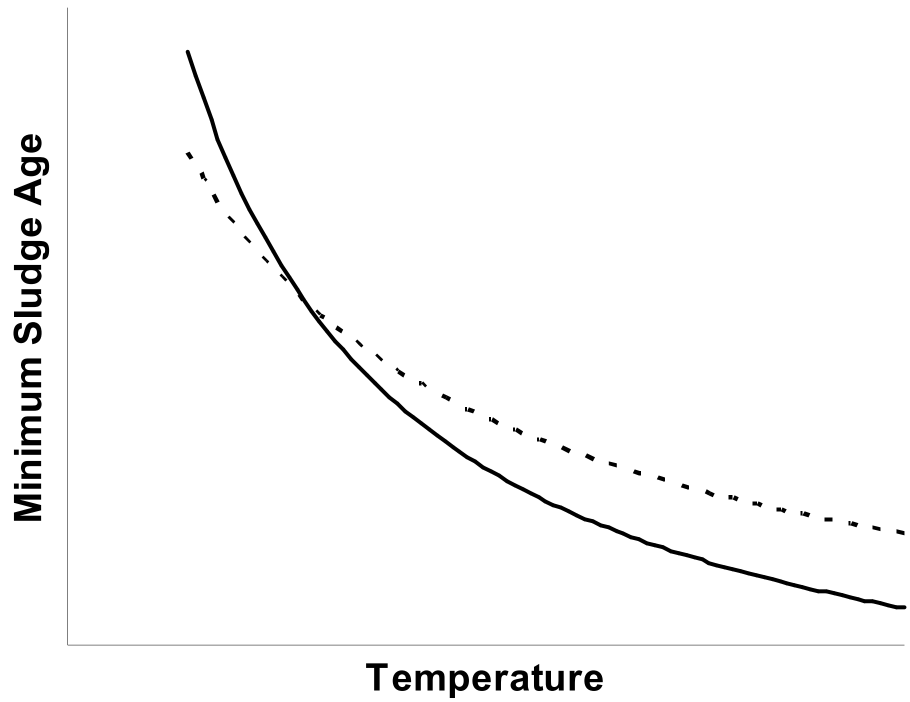

Figure 2-2: AOB minimum required sludge age (—) is lower (due to higher growth rates) than NOB (- - -) at higher temperatures.

The optimal temperature for promoting AOB growth while impeding NOB growth varies in the literature. Hellinga et al. (1998) performed respiration experiments at different temperatures and found an optimum temperature of 40°C for AOB activity. However, they operated at 35°C to ensure process stability. Optimum temperature ranges of 30-36°C (Ford et al., 1980) and above 25°C (Balmelle et al., 1992; Fux et al., 2002) have also been reported.

Aeration Pattern. Intermittent aeration has been used to control the activity of NOB thus limiting the production of NO_3^- (Hidaka et al., 2002; Sasaki et al., 1996; Zhao et al., 1999). In fact, NO_2^- accumulation has been witnessed independent of sludge age when intermittent aeration was used (Pollice et al., 2002). This concept limits the aeration period such that NO_2^- concentrations do not increase substantially past the K_S value of NOB (1.3 mg/L NO_2^--N (Rittmann and McCarty, 2001)) which limits the growth of NOB and prevents the formation of NO_3^-. The NO_2^- produced from AOB is then denitrified to N_2. This process also reduces the concentration of NO_2^- seen by AOB that can be inhibitory to their metabolism (Stein and Arp, 1998).

pH and Inhibitory Compounds. Reported optimum pH ranges for nitrification vary greatly in the literature. It has been generally accepted that bacteria grow poorly outside of the physiological pH range of 6.0 to 8.0 (Grady et al., 1999). However, it has been shown that AOB and NOB growth rates change depending on pH and that AOB specific growth rates peak around 8.0 (Quinlan, 1984).

In addition to affecting the specific growth rate of nitrifying bacteria, pH also affects the concentrations of known inhibitory compounds. Researchers have found that free ammonia (NH_3), nitrous acid (HNO_2), free-hydroxylamine (NH_2OH), and a wide range of organic compounds and acids, heavy metals, and oxidants can inhibit nitrification (Anthonisen et al., 1976; Eilersen et al., 1994; Grunditz et al., 1998; Hao and Chen, 1994; Hockenbury and Grady, 1977). Eilersen et al. (1994) found that volatile fatty acids (VFAs) can inhibit nitrification at high concentrations (Table 2-2). This is important because VFAs are commonly used as carbon sources for denitrification (van Rijn et al., 1996).

Table 2-2. Inhibitory concentrations of VFAs on AOB and NOB activity (mg/L COD).

VFA	AOB	NOB
Formic	-	7,383
Acetic	-	4,366
Proprionic	385	514
n-Butyric	-	2,119
Isobutyric	385	450
n-Valeric	2,375	4,815
Isovaleric	2,311	5,200
n-Caproic	-	7,383

Adapted from (Eilersen et al., 1994)

Researchers have shown that nitrification inhibitors affect AOB and NOB differently and at different concentrations (Peng and Zhu, 2006). In some circumstances, reactor pH can be used to control the concentration of inhibitors with acid/base addition such that the growth rates of NOB are reduced more than AOB, which can result in NO_2^- accumulation. For example, the concentration of free ammonia (FA) is directly related to pH and can be found using the following equation (Anthonisen et al., 1976).

$$NH_3(mg/L-N) = \frac{total-ammonia(mg/L-N)*10^{pH}}{\left(K_b/K_w+10^{pH}\right)}$$ Equation 2-6

Where: $$\frac{K_b}{K_w} = e^{\left(\frac{6344}{273+^oC}\right)}$$ Equation 2-7

Free NH_3 has been known to inhibit both AOB and NOB. However, the inhibitory concentrations vary throughout the literature. Anthonisen et al. (1976) reported that free ammonia inhibits AOB at concentrations ranging from 10-150 mg NH_3-N/L while NOB are inhibited at free ammonia concentrations of 0.1-1 mg NH_3-N.

Using free ammonia to reduce the growth rates of NOB has been successfully used as a strategy to achieve nitritation (Cecen, 1996). However, inconsistencies found in the literature suggest that FA may act in conjunction with other inhibitory compounds to reduce nitrifying activity (Sliekers et al., 2005). Nevertheless, researchers have shown that FA is inhibitory at various levels and mandates strict pH control particularly in systems with high TAN concentrations.

Dissolved Oxygen Concentration. Controlling dissolved oxygen (DO) concentrations is the most frequently studied approach to achieve nitritation and prevent NOB growth, probably due to its simplicity and cost effectiveness. Oxygen half saturation coefficients for AOB and NOB have been studied extensively and have a wide range of reported values (Table 2-3). However, researchers have shown that, on a relative basis, the K_O value for AOBs is less than NOBs corresponding to a higher AOB specific growth rate, μ_{AOB} (day^{-1}) than NOB at low levels of DO (Figure 2-3).

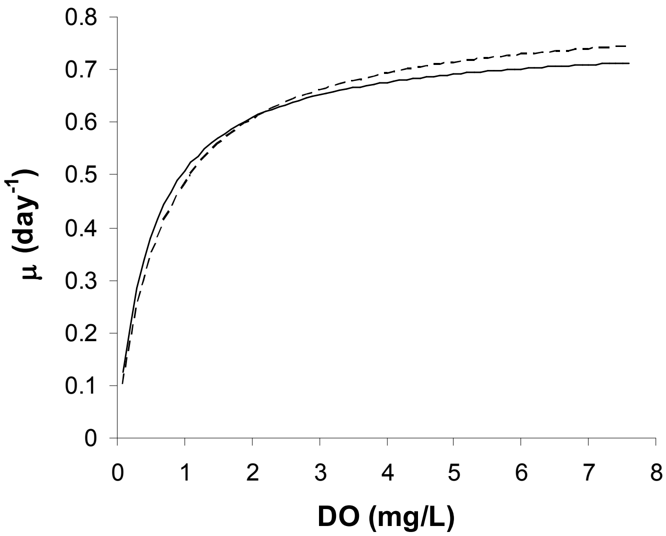

Figure 2-3: The growth rate (μ) for AOB (—) is higher than for NOB (- - -) at lower levels of DO. Curves based on kinetic parameters at 20°C (Rittmann and McCarty, 2001).

Table 2-3 Oxygen half-saturation coefficients (K_O) for AOB and NOB.

AOB K_O (mg/L)	NOB K_O (mg/L)	Source
0.43	1.1	(Wiesmann, 1994)
0.5	0.68	(Rittmann and McCarty, 2001)
0.74 ± 0.02	1.75 ± 0.01	(Guisasola et al., 2005)
0.235	Not given	(Wyffels et al., 2004)

While it is generally understood that AOBs out compete NOBs at low DO concentrations, the optimum DO level needed to achieve nitritation varies throughout the literature (Table 2-4). Sliekers et al. (2005) suggests that the ratio of DO to TAN is the most important factor as opposed to DO concentration alone. A retentostat with sludge retention and an HRT of 4 days was operated at DO and influent TAN concentrations of 2.3 μM O_2 (0.0736 mg/L O_2) and 87.5 mg/L-N, respectively. 99.5% of influent TAN was oxidized and converted to NO_3^- and effluent NO_2^- was negligible. The DO:TAN ratio was then reduced such that the DO and influent TAN were 1 μM O_2 (0.032 mg/L O_2) and 287 mg/L-N, respectively. Under these operating conditions, 77% of removed TAN was oxidized to NO_2^-. However, only half of the influent TAN was oxidized

(Sliekers et al., 2005). This shows the importance of maintaining residual effluent TAN to ensure the competition between AOB and NOB.

Several factors affect the growth kinetics of nitrifying organisms such as: temperature, reactor configuration, pH, waste composition, inhibitory compounds, floc size, and competition with other organisms for common substrates. Therefore, lab and field experiments need to be conducted to determine the optimum DO for achieving nitritation with the waste and reactor configuration that is of interest.

Sludge Age and Hydraulic Retention Time. Low solids retention time (SRT) is typically used in conjunction with other NOB growth-limiting mechanisms to effectively washout the slower growing NOBs. The SHARON process, for instance, uses high temperature to give AOBs a competitive advantage over NOBs. NOBs are then washed out using a low sludge age, typically between 1 and 2.5 days (van Kempen et al., 2001). However, researchers are now achieving nitritation success at higher SRTs. Pollice et al. (2002) ran a lab scale SBR with intermittent aeration (10 min on every 20 min) and was able to show NO_2^- accumulation at SRT values ranging from 3 to 24 days. The NH_4^+ oxidation rates did increase with decreasing SRT values and ranged from 3.2 mg N-NH_4^+ g VSS^{-1} h^{-1} at an SRT of 24 days to 22.9 mg N-NH_4^+ g VSS^{-1} h^{-1} at an SRT of 3 days, but NOB activity was negligible at all SRT values tested (Pollice et al., 2002). The observed decrease in NH_4^+ oxidation rates at higher SRT values were most likely due to NH_4^+ assimilation into biomass due to higher sludge retention. Additionally, nitritation has been reported in systems with retained biomass where SRT cannot be used as a design parameter (Antileo et al., 2006).

Although the SRT equals the HRT in the SHARON and many other nitritation systems, nitritation can be achieved by using a low HRT (less than 2 days) in combination with a longer sludge age (greater than 10 days). Lai et al. (2004) operated a pilot scale nitritation system during the winter months at relatively low temperatures that dropped below 20^{o}C on several occasions. The system was operated with an SRT of 10 days and an initial HRT of 9 days. Nitrate was produced between days 0 to 20, indicating the presence of NOBs. The HRT was gradually reduced to 1.1 days while keeping a sludge age of 10 days. After the decrease in HRT, effluent NO_3^- decreased to 0 while approximately 100% of the removed TAN was accounted for in the NO_2^- form (Lai et al., 2004).

2.2.7 Successful Nitritation Configurations

There has been substantial research over the past several decades on the optimum reactor configuration to promote nitritation. Completely stirred tank reactors (CSTR), sequencing batch reactors (SBR), rotating disc reactors, and membrane biological reactors (MBR), among others, have all been tested and proven by multiple researchers in regards to nitritation (Antileo et al., 2006; Fux et al., 2002; Wyffels et al., 2004) (Table 2-4). Nearly all configurations found in the literature use a combination of the above mentioned methods to select for nitritation. However, 100% TAN removal was not achieved by any of the configurations found in the literature that reported high NO_2^- accumulation. This suggests that NOBs are washed out of nitritation systems through competition with AOBs that are growing at $\hat{\mu}_{AOB}$ in the presence of residual TAN. If TAN is limiting, and AOB are growing at a rate less than $\hat{\mu}_{AOB}$, NOB can perform well at DO concentrations as low as 0.07 mg/L O_2 (Sliekers et al., 2005). This is an important concept that becomes a factor in the research results presented later in this thesis.

Table 2-4: Successful nitritation reactor configurations reported in the literature.

Configuration	SRT (days)	HRT (days)	Temp (°C)	DO (mg/L)	% TAN removal	% NO_2^- (% of NO_3^- + NO_2^-)	Comments	Source
CSTR[a]	1.7	1.7	30-32	2-4	80	93	Operation was best at low HRT values, but process stability was very low. pH regulated the length of aerobic/anoxic zones.	(Fux et al., 2006)
CSTR	--	0.1	30	0.7	93.5	65	NO_2^- accumulation started to take place at a DO of 1.4 mg/L and increased as DO concentration decreased. TAN removal deteriorated at DO = 0.5 mg/L	(Ruiz et al., 2006)
SBR[b]	> 30 days	1 – 1.6	30-32	1.0 – 1.5	94	92	--	(Fux et al., 2006)
SBR with Nit/Denit	--	pH controlled (1.7-0.5)	30	2-3 and reduced to 1.1 – 1.3	96-98	100	NO_3^- build up was never an issue	(Lai et al., 2004)
SBR with Nit/Denit	Range tested: 3-24	3-24	32	Aer 10 min every 20 min	At least 80 %	100	NO_2^- accumulation was observed independent of sludge age. However, the rate of NO_2^- accumulation was greatest at lower sludge ages.	(Pollice et al., 2002)
SBRDR[c]	Retained biomass	--	20	1,0.8, 0.6	21	84, 86, 88	Batch experiments were conducted at DO levels of 1.0, 0.8 and 0.6.	(Antileo et al., 2006)
MBR[d]	Retained biomass	1	30	< 0.1	50	50	System used in combination with an anammox system.	(Wyffels et al., 2004)

[a]completely stirred tank reactor, [b]sequencing batch reactor, [c]sequencing batch rotating disc reactor, [d]membrane bioreactor

2.3 Denitrification

The process by which NO_2^- and NO_3^- are reduced to N_2 is known as heterotrophic denitrification and occurs under anoxic or oxygen-limited conditions (Grady et al., 1999; Kukor and Olsen, 1996). Heterotrophic bacteria use NO_2^- and NO_3^-, and organic carbon sources as terminal electron acceptors and donors, respectively (Equations 2-8 and 2-9). Denitrifying from NO_2^- requires 3 e^- per N atom to reduce the N to $N_{2(g)}$ while denitrifying from NO_3^- requires 5 e^- per N atom. Therefore, denitrifying via NO_2^- uses 40% less heterotrophic electron donor. The organic electron donor (which also serves as the carbon source, ΔS) requirements for denitrification can be determined as follows:

$$\frac{\Delta S}{\Delta NO_2^- - N} = \frac{1.17(1 + b_H\theta_c)}{1 + (b_H\theta_c) - Y_H(1 + f_D b_H \theta_c)}$$ Equation 2-8

:

$$\frac{\Delta S}{\Delta NO_3^- - N} = \frac{2.86(1 + b_H\theta_c)}{1 + (b_H\theta_c) - Y_H(1 + f_D b_H \theta_c)}$$ Equation 2-9

Where the parameters are defined in Table 2-5.

Table 2-5. Equation variables.

Description	Variable	Value
heterotrophic decay rate	b_H	0.18 day^{-1} [1]
Anoxic SRT	θ_c	Variable[2]
heterotrophic growth yield	Y_H	0.6 g COD / g COD[1]
debris fraction of active biomass	f_D	0.2 mg debris COD/mg biomass COD[1]

[1] (Grady et al., 1999)
[2] Actual system anoxic SRT

Organic electron donors commonly used to fuel these reactions in domestic wastewater treatment include: methanol, acetate (and other VFAs), ethanol, lactate, glucose, and many other types of COD (Akunna et al., 1993; Grabinska-Loniewska, 1991; Tam et al., 1992). However, the type of electron donor affects the rates of denitrification and the accumulation of the aqueous and gaseous denitrification intermediates NO_2^-, nitric oxide (NO) and nitrous oxide (N_2O) (Almeida et al., 1995; van Rijn et al., 1996). VAN Rijn et al. (1996) conducted denitrification experiments to test the denitrification rates and NO_2^- accumulation patterns with various VFAs. They found that NO_2^- accumulated when acetate or propionate was used as the sole electron donor but did not accumulate when butyrate, valerate, or caproate was used. Furthermore, the presence of NO_3^- reduces the reduction rate of NO_2^- (van Rijn et al., 1996). Nitrite, $NO_{(g)}$, and $N_2O_{(g)}$ accumulation with certain electron donors is due to the competition for electrons between nitrite and nitrate reductase enzymes (Almeida et al., 1995; Thomsen et al., 1994). Electrons from different carbon sources follow different pathways depending on the electron-transferring proteins that are involved (van Rijn et al., 1996).

Researchers have also shown that AOBs can oxidize TAN to gaseous N_2O under oxygen-limited conditions. Goreau et al. (1980) found that the percent of oxidized TAN accounted for in the $N_2O_{(g)}$ form began to increase as the DO was reduced below 3 mg/L and reached a maximum at a DO of 0.18 mg/L. AOB denitrification may be present even when measured DO values are above those found in literature. This is because microaerobic zones can occur in wastewater treatment plants, particularly those that treat wastes with high solids concentrations and floc size such as animal waste. Microaerobic zones can create an environment that is ideal for a process known as simultaneous nitrification-denitrification.

2.4 Simultaneous Nitrification-Denitrification and Novel Microorganisms

Under oxygen limited conditions, TAN can be oxidized to NO_2^- and NO_3^- (Section 2.2.1). Anoxic zones within the aerated bioreactor then allow for NO_2^- and NO_3^- to be simultaneously denitrified to N_2 gas which is referred to as simultaneous nitrification-denitrification (SND). Daigger and Littleton (2000) suggest that the three mechanisms responsible for SND are:

1. bioreactor macroenvironment

2. floc microenvironment
3. novel microorganisms

The bioreactor macroenvironment refers to the mixing, aeration pattern, and operation schematic of the bioreactor that could create both aerobic and anoxic zones within the same basin. The floc microenvironment refers to the scenario where oxygen diffusivity restraints create micro zones within sludge flocs that are anoxic and allow for SND. Finally, novel microorganisms may contribute to high N losses in SND treatment plants.

Novel metabolisms exhibited by some unique microorganisms include: autotrophic denitrification (Bock et al., 1995), heterotrophic nitrification (Geraats et al., 1990), aerobic denitrification (Robertson et al., 1995) and denitrification by phosphate accumulating organisms (Filipe and Daigger, 1999). Daigger and Littleton tested the contribution that novel microorganisms had on N loss in wastewater treatment plants known for simultaneous nutrient removal. They found that novel microorganisms had a minimal effect on the N removal exhibited by SND systems (Littleton et al., 2003). Therefore, SND is most likely performed by conventional aerobic, autotrophic nitrifying microorganisms and anoxic, heterotrophic denitrifying microorganisms under low oxygen conditions.

2.5 Fermentation

The fermentation and degradation of organic substrates follows a multi-step anaerobic process that involves four complex steps and five distinct groups of microorganisms. The first stage, hydrolysis, refers to the process by which complex, insoluble substrates such as polysaccharides, lipids, and proteins are converted (hydrolyzed) by fermentative bacteria into the simpler substrates of simple sugars, fatty acids and amino acids. Fermentative bacteria then ferment the hydrolysis products into a mixture of organic acids and alcohols. The third stage, acidogenesis, is accomplished by obligatory hydrogen-producing acetogenic bacteria that use the products from fermentation as reactants to produce hydrogen and acetate. Acetate is also produced from hydrogen and CO_2 by acetogens and homoacetogens. The final stage is called methanogenesis and is the metabolism by which CH_4 is produced from acetate or methanol by acetoclastic methanogens, or by the combination of H_2 and CO_2 by hydrogenotrophic methanogens (Angenent et al., 2004; Angenent et al., 2002; Grady et al., 1999).

The products of hydrolysis and fermentation, namely VFAs, are excellent sources of readily biodegradable COD and can be used as an external energy source for heterotrophic, denitrifying organisms (Fass et al., 1994). Furthermore, VFAs are more cost effective than other carbon sources such as methanol because they can be biologically produced on-site (Eilersen et al., 1994). However, the microorganisms responsible for VFA production typically co-exist with methanogens that consume VFAs to produce methane. In order to accumulate VFAs, the growth of methanogens must be impeded.

A variety of techniques and configurations have been reported in the literature for maximizing VFA production. These include chemical inhibition using 2-bromoethanesulfonic acid (BESA) and 2-chloroethanesulfonic acid (CESA) or the addition of acetylene in the headspace (Valdez-Vazquez, 2005), pH, and SRT. Of the techniques listed, pH and SRT are the most cost effective techniques for accumulating VFAs.

The optimum reactor pH required for VFA production varies in the literature between 6-8 (Xian-Jun and Han-Qing, 2004; Zeng et al., 2006). Optimum SRT values also vary greatly in the literature. Ranges of 6-8 days (Bouzas et al., 2007), 4 days (Chen et al., 2004), 4-5 days (Chanona et al., 2006), 2-3 days (Grady et al., 1999), and 3-4 days (Yanosek, 2002) have been reported for optimum VFA production from fermentation.

2.6 Kinetic Parameters and Modeling

In recent years, kinetic modeling software packages such as Biowin® from Envirosim Associates, Ltd. have allowed designers to model biological processes and determine key reactor parameters. However, the model uses typical kinetic values based on a standard influent wastewater. These models are flexible and allow for the adjustment of key kinetic parameters. In terms of nitrification, the key parameters for AOBs and NOBs are given in Tables 2-6 and 2-7, respectively. The tabulated values for the kinetic parameters have been measured for a variety of wastewaters and reported in the literature. Default parameter values are also listed from the BioWin® (Envirosim Associates, Ltd.) simulation software package used in this research. The default values were used to assess the probable performance of a N removal system treating solids separated, fermented dairy manure as part of this study.

Table 2-6: Kinetic parameter values for AOB found in the literature.

AOB Parameters	Biowin® default	Literature value
Yield (mg COD / mg N)	0.15	0.47*, 0.18#
Substrate (NH_4^+) half saturation mgN/L	0.7	1.0*
Aerobic decay rate (1/d)	0.17	0.11*
Anoxic/Anaerobic decay rate (1/d)	0.08	
Max specific growth rate (1/d)	0.90	0.76*, 0.32+, 1.4#

*(Rittmann and McCarty, 2001), +(Jang et al., 2005), #(Hunik et al., 1994),

Table 2-7: Kinetic parameter values for NOB found in the literature.

NOB Parameters	Biowin default	Literature value
Yield (mg COD / mg N)	0.09	0.12*, 0.06#
Substrate (NO_2^-) half saturation mgN/L	0.05	1.3*, 2•
Aerobic decay rate (1/d)	0.17	0.11*
Anoxic/Anaerobic decay rate (1/d)	0.08	
Max specific growth rate (1/d)	0.7	0.81*, 0.9#

*(Rittmann and McCarty, 2001), #(Hunik et al., 1994), •(Moussa et al., 2005)

2.7 References

Ahn, Y. H. and Choi, H. C. (2006). Autotrophic nitrogen removal from sludge digester liquids in upflow sludge bed reactor with external aeration. *Process Biochemistry*, **41**(9), 1945-1950.

Akunna, J. C., Bizeau, C. and Moletta, R. (1993). Nitrate and nitrite reductions with anaerobic sludge using various carbon sources: Glucose, glycerol, acetic acid, lactic acid and methanol. *Water Research*, **27**(8), 1303-1312.

Almeida, J. S., Reis, M. A. M. and Carrondo, M. J. T. (1995). Competition between nitrate and nitrite reduction in denitrification by *Pseudomonas fluorescens*. *Biotechnology and Bioengineering*, **46**(5), 476-484.

Angenent, L. T., Karim, K., Al-Dahhan, M. H. and Domiguez-Espinosa, R. (2004). Production of bioenergy and biochemicals from industrial and agricultural wastewater. *Trends in Biotechnology*, **22**(9), 477-485.

Angenent, L. T., Sung, S. and Raskin, L. (2002). Methanogenic population dynamics during startup of a full-scale anaerobic sequencing batch reactor treating swine waste. *Water Research*, **36**(18), 4648-4654.

Anthonisen, A. C., Loehr, R. C., Prakasam, T. B. S. and Srinath, E. G. (1976). Inhibition of nitrification by ammonia and nitrous acid. *Journal Water Pollution Control Federation*, **48**(5), 835-852.

Antileo, C., Werner, A., Ciudad, G., Munoz, C., Bornhardt, C., Jeison, D. and Urrutia, H. (2006). Novel operational strategy for partial nitrification to nitrite in a sequencing batch rotating disk reactor. *Biochemical Engineering Journal*, **32**(2), 69-78.

Balmelle, B., Nguyen, K. M., Capdeville, B., Cornier, J. C. and Deguin, A. (1992). Study of factors controlling nitrite buildup in biological processes for water nitrification. *Water Science and Technology*, **26**(5-6), 1017-1025.

Bock, E., Koops, H. P. and Harms, H. (1986). *Cell Biology of Nitrifying Bacteria.* IRL Press, Oxford, Washington, D.C.

Bock, E., Schmidt, I., Stuven, R. and Zart, D. (1995). Nitrogen loss caused by denitrifying *Nitrosomonas* cells using ammonium or hydrogen as electron-donors and nitrite as electron-acceptor. *Archives of Microbiology*, **163**(1), 16-20.

Bouzas, A., Ribes, J., Ferrer, J. and Seco, A. (2007). Fermentation and elutriation of primary sludge: Effect of SRT on process performance. *Water Research*, **41**(4), 747-756.

Cecen, F. (1996). Investigation of partial and full nitrification characteristics of fertilizer wastewaters in a submerged biofilm reactor. *Water Science and Technology*, **34**(11), 77-85.

Chanona, J., Ribes, J., Seco, A. and Ferrer, J. (2006). Optimum design and operation of primary sludge fermentation schemes for volatile fatty acids production. *Water Research*, **40**(1), 53-60.

Chen, W., Steen, F. M. and Green, P. G. (2004). Key influential factors for sludge prefermentation process design - a case study. *Environmental Technology*, **25**(4), 381-390.

Daigger, G. T. and Littleton, H. X. (2000). Characterization of Simultaneous Nutrient Removal in Staged, Closed-Loop Bioreactors. *Water Environment Research*, **72**, 330-339.

Eilersen, A. M., Henze, M. and Kloft, L. (1994). Effect of volatile fatty acids and trimethylamine on nitrification in activated sludge. *Water Research*, **28**(6), 1329-1336.

Fass, S., Ganaye, V., Urbain, V., Manem, J. and Block, J. C. (1994). Volatile Fatty-Acids As Organic-Carbon Sources In Denitrification. *Environmental Technology*, **15**(5), 459-467.

Fdz-Polanco, F., Villaverde, S. and Garcia, P. A. (1996). Nitrite accumulation in submerged biofilters - combined effects. *Water Science and Technology*, **34**(3-4), 371-378.

Filipe, C. D. M. and Daigger, G. T. (1999). Evaluation of the capacity of phosphorus-accumulating organisms to use nitrate and oxygen as final electron acceptors: A theoretical study on population dynamics. *Water Environment Research*, **71**(6), 1140-1150.

Ford, D. L., Churchwell, R. L. and Kachtick, J. W. (1980). Comprehensive analysis of nitrification of chemical processing wastewaters. *Journal Water Pollution Control Federation*, **52**(11), 2726-2746.

Fux, C., Boehler, M., Huber, P., Brunner, I. and Siegrist, H. (2002). Biological treatment of ammonium-rich wastewater by partial nitritation and subsequent anaerobic ammonium oxidation (anammox) in a pilot plant. *Journal of Biotechnology*, **99**(3), 295-306.

Fux, C., Velten, S., Carozzi, V., Solley, D. and Keller, J. (2006). Efficient and stable nitritation and denitritation of ammonium-rich sludge dewatering liquor using an SBR with continuous loading. *Water Research*, **40**(14), 2765-2775.

Geraats, S. G. M., Hooijmans, C. M., Vanniel, E. W. J., Robertson, L. A., Heijnen, J. J., Luyben, K. and Kuenen, J. G. (1990). The use of a metabolically structured model in the study of growth, nitrification, and denitrification by *Thiosphaera pantotropha*. *Biotechnology and Bioengineering*, **36**(9), 921-930.

Goreau, T. J., Kaplan, W. A., Wofsy, S. C., McElroy, M. B., Valois, F. W. and Watson, S. W. (1980). Production of NO_2^- and N_2O by nitrifying bacteria at reduced concentrations of oxygen. *Applied and Environmental Microbiology*, **40**(3), 526-532.

Grabinska-Loniewska, A. (1991). Denitrification unit biocenosis. *Water Research*, **25**(12), 1565-1573.

Grady, L. C., Daigger, G. T. and Lim, H. C. (1999). *Biological Wastewater Treatment*. Marcel Dekker, Inc., New York, NY.

Grunditz, C., Gumaelius, L. and Dalhammar, G. (1998). Comparison of inhibition assays using nitrogen removing bacteria: Application to industrial wastewater. *Water Research*, **32**(10), 2995-3000.

Guisasola, A., Jubany, I., Baeza, J. A., Carrera, J. and Lafuente, J. (2005). Respirometric estimation of the oxygen affinity constants for biological ammonium and nitrite oxidation. *Journal of Chemical Technology and Biotechnology*, **80**(4), 388-396.

Hao, O. and Chen, J. (1994). Factors affecting nitrite buildup in submerged filter system. *Journal of Environmental Engineering-ASCE* **120**(5), 1298-1307.

Hellinga, C., Schellen, A. A. J. C., Mulder, J. W., van Loosdrecht, M. C. M. and Heijnen, J. J. (1998). The SHARON process: An innovative method for nitrogen removal from ammonium-rich waste water. *Water Science and Technology*, **37**(9), 135-142.

Herbst, R. (2002). The State of the Chesapeake Bay. Chesapeake Bay Program of the U.S. Environmental Protection Agency. 903-R-02-002.

Hidaka, T., Yamada, H., Kawamura, M. and Tsuno, H. (2002). Effect of dissolved oxygen conditions on nitrogen removal in continuously fed intermittent-aeration process with two tanks. *Water Science and Technology*, **45**(12), 181-188.

Hockenbury, M. and Grady, C. (1977). Inhibition of nitrification - effects of selected organic compounds. *Journal of Water Pollution Control Federation*, **49**, 768-777.

Hunik, J. H., Bos, C. G., Vandenhoogen, M. P., Degooijer, C. D. and Tramper, J. (1994). Co-immobilized *Nitrosomonas europaea* and *Nitrobacter agilis* cells - Validation of a dynamic model for simultaneous substrate conversion and growth in *Kappa carrageenan* gel beads. *Biotechnology and Bioengineering*, **43**(11), 1153-1163.

Jang, A., Okabe, S., Watanabe, Y., Kim, I. S. and Bishop, P. L. (2005). Measurement of growth rate of ammonia oxidizing bacteria in partially submerged rotating biological contactor by fluorescent in situ hybridization (FISH). *Journal of Environmental Engineering and Science*, **4**(5), 413-420.

Jetten, M. S. M., Strous, M., van de Pas-Schoonen, K. T., Schalk, J., van Dongen, U., van de Graaf, A. A., Logemann, S., Muyzer, G., van Loosdrecht, M. C. M. and Kuenen, J. G. (1998). The anaerobic oxidation of ammonium. *FEMS Microbiology Reviews*, **22**(5), 421-437.

Jetten, M. S. M., Wagner, M., Fuerst, J., van Loosdrecht, M., Kuenen, G. and Strous, M. (2001). Microbiology and application of the anaerobic ammonium oxidation (`anammox') process. *Current Opinions in Biotechnology*, **12**(3), 283-288.

Khin, T. and Annachhatre, A. P. (2004). Novel microbial nitrogen removal processes. *Biotechnology Advances*, **22**(7), 519-532.

Khanal, S. K., Chen, W.H., Li, L., and Sung, S. (2006). Biohydrogen production in continuous-flow reactor using mixed microbial culture. *Water Environment Research*, **78**(2), 110-118.

Knowlton, K. F., Love, N. G. and Parsons, C. M. (2005). Dietary phosphorus effects on characteristics of mechanically separated dairy manure. *Transactions of the ASAE*, **48**(3), 1253-1258.

Kuai, L. and Verstraete, W. (1998). Ammonium removal by the oxygen-limited autotrophic nitrification-denitrification system. *Applied and Environmental Microbiology*, **64**(11), 4500-4506.

Kukor, J. J. and Olsen, R. H. (1996). Catechol 2,3-dioxygenases functional in oxygen-limited (hypoxic) environments. *Applied and Environmental Microbiology*, **62**(5), 1728-1740.

Lai, E., Senkpiel, S., Solley, D. and Keller, J. (2004). Nitrogen removal of high strength wastewater via nitritation/denitritation using a sequencing batch reactor. *Water Science and Technology*, **50**(10), 27-33.

Littleton, H. X., Daigger, G. T., Strom, P. F. and Cowan, R. A. (2003). Simultaneous biological nutrient removal: evaluation of autotrophic denitrification, heterotrophic nitrification, and biological phosphorus removal in full-scale systems. *Water Environment Research*, **75**(2), 138-150.

Moussa, M. S., Hooijmans, C. M., Lubberding, H. J., Gijzen, H. J. and Loosdrecht, M. C. M. v. (2005). Modeling nitrification, heterotrophic growth and predation in activated sludge. *Water Research*, **39**, 5080-5098.

Mulder, J. W., van Loosdrecht, M. C. M., Hellinga, C. and van Kempen, R. (2001). Full-scale application of the SHARON process for treatment of rejection water of digested sludge dewatering. *Water Science and Technology*, **43**(11), 127-134.

Peng, Y. and Zhu, G. (2006). Biological nitrogen removal with nitrification and denitrification via nitrite pathway. *Applied Microbiology and Biotechnology*, **73**(1), 15-26.

Picioreanu, C., van Loosdrecht, M. C. M. and Heijnen, J. J. (1997). Modelling the effect of oxygen concentration on nitrite accumulation in a biofilm airlift suspension reactor. *Water Science and Technology*, **36**(1), 147-156.

Pollice, A., Tandoi, V. and Lestingi, C. (2002). Influence of aeration and sludge retention time on ammonium oxidation to nitrite and nitrate. *Water Research*, **36**(10), 2541-2546.

Quinlan, A. V. (1984). Prediction of the optimum pH for ammonia-n oxidation by nitrosomonas Europaea in well-aerated natural and domestic-waste waters. *Water Research*, **18**(5), 561-566.

Reynolds, T. D. and Richards, P. A. (1996). *Unit Operations and Processes in Environmental Engineering*. *2nd ed*. PWS Publishing, Washington, D.C.

Rittmann, B. E. and McCarty, P. L. (2001). *Environmental Biotechnology: Principles and Applications*. Thomas Casson, New York, NY.

Robertson, L. A., Dalsgaard, T., Revsbech, N.-P. and Kuenen, J. G. (1995). Confirmation of `aerobic denitrification' in batch cultures, using gas chromatography and ^{15}N mass spectrometry. *FEMS Microbiology Ecology*, **18**(2), 113-119.

Ruiz, G., Jeison, D. and Chamy, R. (2003). Nitrification with high nitrite accumulation for the treatment of wastewater with high ammonia concentration. *Water Research*, **37**(6), 1371-1377.

Ruiz, G., Jeison, D., Rubilar, O., Ciudad, G. and Chamy, R. (2006). Nitrification-denitrification via nitrite accumulation for nitrogen removal from wastewaters. *Bioresource Technology*, **97**(2), 330-335.

Sasaki, K., Yamamoto, Y., Tsumura, K., Ouchi, S. and Mori, Y. (1996). Development of 2 reactor intermittent-aeration activated sludge process for simultaneous removal of nitrogen and phosphorus. *Water Science and Technology*, **34**(1-2), 111-118.

Sliekers, A. O., Derwort, N., Gomez, J. L. C., Strous, M., Kuenen, J. G. and Jetten, M. S. M. (2002). Completely autotrophic nitrogen removal over nitrite in one single reactor. *Water Research*, **36**(10), 2475-2482.

Sliekers, A. O., Haaijer, S. C. M., Stafsnes, M. H., Gijs Kuenen, J. and Jetten, M. S. M. (2005). Competition and coexistence of aerobic ammonium- and nitrite-oxidizing bacteria at low oxygen concentrations. *Applied Microbiology and Biotechnology*, **68**(6), 808-817.

Stein, L. Y. and Arp, D. J. (1998). Loss of ammonia monooxygenase activity in *Nitrosomonas europaea* upon exposure to nitrite. *Applied Environmental Microbiology*, **64**(10), 4098-4102.

Stuven, R., Vollmer, M. and Bock, E. (1992). The impact of organic matter on nitric oxide formation by *Nitrosomonas europaea*. *Archives of Microbiology*, **158**, 439-443.

Tam, N. F. Y., Wong, Y. S. and Leung, G. (1992). Effect of exogenous carbon sources on removal of inorganic nutrient by the nitrification-denitrification process. *Water Research*, **26**(9), 1229-1236.

Tchobanoglous, G., Burton, F. L. and Stensel, H. D. (2003). *Wastewater Engineering: Treatment and Reuse*. *4th ed*. Metcalf and Eddy, McGraw-Hill, Boston.

Third, K. A., Sliekers, A. O., Kuenen, J. G. and Jetten, M. S. M. (2001). The CANON system (completely autotrophic nitrogen removal over nitrite) under ammonium limitation: Interaction and competition between three groups of bacteria. *Systematic and Applied Microbiology*, **24**(4), 588-596.

Thomsen, J. K., Geest, T. and Cox, R. P. (1994). Mass spectrometric studies of the effect of pH on the accumulation of intermediates in denitrification by *Paracoccus denitrificans*. *Applied and Environmental Microbiology.*, **60**(2), 536-541.

Turk, O. and Mavinic, D. S. (1989). Maintaining nitrite build-up in a system acclimated to free ammonia. *Water Research*, **23**(11), 1383-1388.

USDA. (1992). Agricultural Waste Characteristics. In *Agricultural Waste Management Field Handbook*, ed. USDA, pp. 1-24.

Valdez-Vazquez, I., Sparling, R., Risbey, D., Rinderknecht-Seijas, N., and Poggi-Varaldo, H. M. (2005). Hydrogen generation via anaerobic fermentation of paper mill wastes. *Bioresource Technology*, **96**, 1907-1913.

Van Horn, H. H., Wilkie, A. C., Powers, W. J. and Nordstedt, R. A. (1994). Components of dairy manure management systems. *Journal of Dairy Science*, 77, 2008-2030.

van Kempen, R., Mulder, J. W., Uijterllnde, C. A. and van Loosdrecht, M. C. M. (2001). Overview: full scale experience of the SHARON process for treatment of rejection water of digested sludge dewatering. *Water Science and Technology*, **44**(1), 145-152.

van Rijn, J., Tal, Y. and Barak, Y. (1996). Influence of volatile fatty acids on nitrite accumulation by a *Pseudomonas stutzeri* strain isolated from a denitrifying fluidized bed reactor. *Applied and Environmental Microbiology*, **62**(7), 2615-2620.

vandeGraaf, A. A., deBruijn, P., Robertson, L. A., Jetten, M. S. M. and Kuenen, J. G. (1997). Metabolic pathway of anaerobic ammonium oxidation on the basis of N-15 studies in a fluidized bed reactor. *Microbiology-UK*, **143**, 2415-2421.

Wiesmann, U. (1994). Biological nitrogen removal from wastewater. *Advances in Biochemical Engineering, Biotechnology*, **51**, 113.

Wyffels, S., Van Hulle, S. W. H., Boeckx, P., Volcke, E. I. P., Van Cleemput, O., Vanrolleghem, P. A. and Verstraete, W. (2004). Modeling and simulation of oxygen-limited partial nitritation in a membrane-assisted bioreactor (MBR). *Biotechnology and Bioengineering*, **86**(5), 531-542.

Xian-Jun, Z. and Han-Qing, Y. (2004). Roles of pH in biologic production of hydrogen and volatile fatty acids from glucose by enriched anaerobic cultures. *Applied Biochemistry and Biotechnology*, **112**, 79-90.

Yanosek, K. A. (2002). Enhanced Biological Phosphorus Removal From Dairy Manure to Meet Nitrogen:Phosphorus Crop Nutrient Requirements. Masters of Science, Virginia Polytechnic Institute and State University. Blacksburg, VA, pp. 229.

Yoo, H., Ahn, K.-H., Lee, H.-J., Lee, K.-H., Kwak, Y.-J. and Song, K.-G. (1999). Nitrogen removal from synthetic wastewater by simultaneous nitrification and denitrification (SND) via nitrite in an intermittently-aerated reactor. *Water Research*, **33**(1), 145-154.

Zeng, R. J., Yuan, Z. and Keller, J. (2006). Effects of solids concentration, pH and carbon addition on the production rate and composition of volatile fatty acids in prefermenters using primary sewage sludge. *Water Science and Technology*, **53**(8), 263-269.

Zhao, H. W., Mavinic, D. S., Oldham, W. K. and Koch, F. A. (1999). Controlling factors for simultaneous nitrification and denitrification in a two-stage intermittent aeration process treating domestic sewage. *Water Research*, **33**(4), 961-970.

3 OPTIMIZATION OF BIOLOGICAL NITROGEN REMOVAL FROM FERMENTED DAIRY MANURE USING LOW LEVELS OF DISSOLVED OXYGEN

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3.1 Abstract

The objective of this research was to determine the feasibility of removing total ammonia-N (TAN) from dairy manure by using nitritation combined with denitrification of fermented dairy manure in an N removal, pilot scale system. A fermenter located upstream of the N removal system, provided volatile fatty acids (VFAs) and TAN at a chemical oxygen demand (COD):TAN ratio of 18:1. Sufficient non-VFA electron donor was present in the fermenter effluent to support denitrification. Complete TAN removal was observed at DO concentrations as low as 0.8 mg/L but at N removal rates that were less than expected based on models using typical kinetic parameters for ammonia oxidizing bacteria. These results indicate the presence of a nitrification inhibitor in the fermented dairy manure. Finally, an N balance shows that simultaneous nitrification-denitrification was present in the N removal system and was most apparent at DO concentrations below 1.3 mg/L.

Keywords

nitritation, deammonification, denitrification, nitrogen removal, dairy manure treatment, fermentation, simultaneous nitrification denitrification.

3.2 Introduction

Agriculture is the largest contributor of non-point source pollution in nearly all watersheds of North America. For example, agriculture, including animal feeding operations (AFOs), contributes 38 percent of the total nitrogen (N) load into the Chesapeake Bay, located on the east coast of the United States, compared to 20 percent contributed by point sources (Herbst, 2002). Because N can be harmful to water quality when present in excess, it is appropriate to implement cost effective nutrient treatment strategies to ensure the health of water bodies and the environments that surround them.

Dairy manure contains large concentrations of nutrients and organics that can pollute the environments surrounding dairy operations. Larger dairies increasingly use solid separation to remove suspended solids from manures. Mechanical separation produces two waste streams (solid and liquid) that both contain high levels of N (Knowlton et al., 2005; Van Horn et al., 1994). The research conducted for this study focused on N removal from the liquid waste stream of the solids separation process. While dairies often apply the N in manures as a fertilizer, many manures contain N in excess of what is needed. Additionally, TAN present in manure is problematic because it readily volatilizes, leading to air quality degradation (Amon et al., 2006).

Liquid effluent from dairy waste separators contains organics and nutrients at levels that are orders of magnitude higher than those found in municipal wastewater (Table 3-1). Also, AFOs do not have access to the same resources as municipalities to treat their waste. Therefore, innovative technologies must be implemented that are both cost effective and practical for AFOs.

Table 3-1: Dairy manure and municipal wastewater characteristics.

Constituent	Dairy liquid separator effluent[1]	Municipal[2]
TAN (mg/L-N)	840	25
TKN (mg/L)	3,080	40
Total P (mg/L)	300	7
Total COD (mg/L)	37,500	430

[1](Knowlton et al., 2005)
[2]Values for medium strength municipal wastewater (Tchobanoglous et al., 2003)

Nitrogen primarily exists in the reduced form (organic N or inorganic TAN) in dairy waste (Knowlton et al., 2005). Biological N removal is typically not a goal in dairy waste management systems, despite the existence of some farms that would benefit from achieving N removal. Conventional biological nutrient removal (BNR) systems applied to domestic wastewater remove inorganic N through a multiple step process. The reduced N is first oxidized under aerobic conditions by two distinct groups of bacteria: ammonia oxidizing bacteria (AOB) convert TAN to nitrite (NO_2^-), and nitrite oxidizing bacteria (NOB) convert NO_2^- to nitrate (NO_3^-). NO_3^- can be subsequently reduced as an electron acceptor under anoxic conditions to N_2 by denitrification, which is typically fueled by organic electron donors.

Modifications to conventional BNR can be implemented to remove N in a more cost effective way. One such technique is known as nitritation coupled with denitritation where TAN is partially oxidized aerobically to NO_2^- and then denitrified under anoxic conditions to N_2. This metabolism is accomplished by limiting the growth of NOB, which prevents the oxidation of NO_2^- to NO_3^-. Removing N via NO_2^- as opposed to NO_3^- reduces aeration requirements by 25% (van Kempen et al., 2001), requires 40% less carbon source for denitrification (Ruiz et al., 2003), and improves denitrification rates (Turk and Mavinic, 1989; van Rijn et al., 1996).

The growth of NOB can be controlled using several different methods, including: high reactor temperatures (Hellinga et al., 1998); low solids retention time (SRT) (van

Kempen et al., 2001); chemical inhibition; and low dissolved oxygen (DO) concentrations (Ruiz et al., 2003). Due to their high costs, chemical addition and heat are not practical strategies for controlling NOB growth at AFOs. Therefore, DO control is much more feasible for application in AFO systems. AOBs are known to outcompete NOBs at DO concentrations less than 1 mg/L (Ruiz et al., 2006). Researchers have shown that AOB can reduce NO_2^- to N_2O, a harmful greenhouse gas, under oxygen-limited conditions in a process known as autotrophic denitrification (Tallec et al., 2006). Nevertheless, by maintaining a low concentration of DO in a manure treatment system, N removal may be achieved in AFOs.

The objective of this research was to determine the minimum DO concentration required to sustain TAN removal via NO_2^- from solids-separated, scraped dairy waste. Furthermore, Volatile fatty acids (VFAs) produced through the anaerobic fermentation of solids-separated dairy manure are an inexpensive and sustainable electron donor source for use in AFO N removal, and are demonstrated in this study.

3.3 Methods

3.3.1 Construction, design and operation of reactor system

A two step reactor system, shown schematically in Figure 3-1 and described in Table 3-2, was constructed and maintained in a shed located at the Virginia Tech Dairy. The system consisted of a fermenter followed by an N removal reactor and was controlled by automated timers and monitoring devices, as described below for each component of the system.

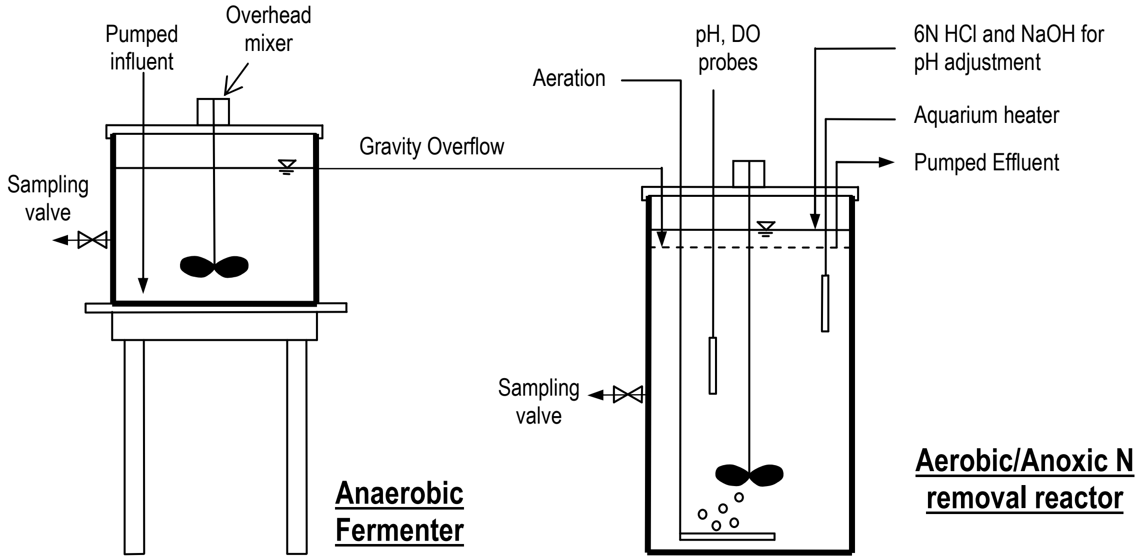

Figure 3-1. Pilot scale system. Including upstream fermenter and downstream N removal reactor.

Table 3-2. Pilot scale system configuration and operation.

Reactor Parameter	Fermenter	N removal
Volume	30 L	150 L
Operation	Anaerobic	Anoxic/Aerobic/Anoxic
SRT	2 days	10 days
% Aeration Time	--	65 %
Aerobic SRT	--	6.5 days
Temperature	Not Controlled	22-26 ^{o}C
pH	Not Controlled	7.0 – 7.3

3.3.2 Fermentation systems

Prior to implementing fermentation at the pilot scale, an 8 L laboratory scale anaerobic fermentation reactor was constructed and operated for 85 days to determine operating conditions that would maximize VFA production for use as an external carbon source for denitritation. The laboratory fermenter was operated as a sequencing batch reactor (SBR). The reactor was seeded with 2 L of anaerobically digester sludge and 2 L of return activated sludge (RAS) from the Town of Christiansburg Wastewater Treatment

Plant (CWWTP) and 4 L of system feed as described in section 3.3.4. The fermenter was operated with a hydraulic retention time (HRT) and SRT equal to 2 days to promote fermentation but prevent methanogenesis. Samples were analyzed for total and volatile suspended solids (TSS, VSS) and NH_3 according to methods 2540 D and E and 4500-NH_3 F, respectively, as described in Standard Methods (APHA, 1998). Additionally, samples were measured for VFA concentrations using a Hewlett Packard 5890 A Series gas chromatograph equipped with a flame ionization detector (FID) and a Nukol fused silica capillary column 15m x 0.53mm ID x 0.5 μm film thickness (Supelco, Inc. Bellefonte, PA). VFA data analysis was performed using a Dionex workstation with Peaknet 6.0 Chromeleon software (Dionex Corporation, Sunnyvale, CA, USA). The measured performance characteristics of the fermenter were used in the Biowin® (EnviroSim Associates, Ltd.) version 3.0 simulator to help determine the best initial configuration for the pilot scale system.

Once the lab-scale system was demonstrated experimentally, a 30 L pilot-scale fermenter was constructed as part of the two-step AFO N removal treatment system (Figure 3-1). The fermenter was seeded with 7.5 L of anaerobically digested sludge and 7.5 L RAS from CWWTP, as for the laboratory fermenter, and 15 L system feed (Section 3.3.4). After inoculation, the system was operated semi-continuously by pumping 5 L of refrigerated, solids-separated feed (described below) 3 times per day to mimic the typical scraping frequency of a scraped dairy operation (MWPS, 1993). Separating HRT and SRT requires the addition of recycle pumps, which may not be economical for AFOs. Therefore, the HRT was set equal to the SRT at 2 days in the fermenter. Effluent from this reactor flowed by gravity into the N removal reactor.

3.3.3 Pilot scale N removal reactor

A Biowin® (EnviroSim Associates, Ltd.) modeling simulation package (version 3.0) was used with default parameter settings to define the initial operating strategy (SRT and percent aeration) for the N removal reactor. The model feed was characterized using the measured concentrations obtained from the laboratory-scale fermenter results and those reported by Knowlton et al (2005). Total SRT values of 2, 4, 6 and 8 days were simulated for the N removal reactor. Dynamic model simulations were run for each SRT while varying the percent aeration. A total SRT and percent aeration of 6 days and 35%, respectively were initially selected based on the simulated results (Appendix Section A.1) and agreed with similar values found in the literature (Ruiz et al., 2003; van Kempen et al., 2001). However, the system operating conditions were later increased to 10 days total SRT and 65% aerobic SRT due to poor performance by the pilot scale system. The results given in this paper focus on the latter operating conditions, which were initiated on operating day 98. Furthermore, the poor predictive power of the initial simulation indicates that the default parameters for Biowin® 3.0 are not appropriate for simulating dairy waste treatment and requires recalibration. We report on an effort to recalibrate Biowin® 3.0 for application to dairy waste elsewhere (Beck et al., 2007).

The N removal reactor was seeded with 130 L of RAS collected from the Blacksburg VPI wastewater treatment plant in Blacksburg, VA. The completely mixed N removal reactor was alternated between anoxic, aerobic and a second anoxic phase within each cycle (3 cycles per day) to facilitate nitritation and denitritation. Specifically, five liters of fermented effluent gravity flowed into the N removal reactor at the beginning of the first anoxic (denitritation) phase which lasted for 1 hour and 10 minutes. Next, aeration was initiated to achieve different, controlled levels of DO and was sustained for 5 hours and 10 minutes (65% of the total 8 hour cycle). The final denitritation phase lasted 1 hour and 40 minutes. The cycle was completed by removing 5 L of well mixed biomass from the N removal reactor effluent. In total, each reactor cycle lasted 8 hours. Insufficient temperature, DO, and pH control during the first 98 days of operation required the reactor to be reseeded on day 98.

After day 98, DO and pH were controlled by a Hach® sc100™ controller connected to a Hach® differential pH digital sensor probe and a Hach® luminescent dissolved oxygen (LDO) probe (Hach® Company: Loveland, CO, USA). The pH was kept between 7.0 and 7.3 by adding 6 N HCl or 6 N NaOH to decrease or increase the pH, respectively. This range was chosen to minimize free NH_3 concentrations to below 10 mg/L to avoid inhibition of AOB (Anthonisen et al., 1976). Two Chrontrol® timers (4 circuit model

XT-4, Chrontrol Corporation: San Diego, CA, USA) were used to control feeding and aeration equipment. An air compressor (Gast manufacturing: Benton Harbor, MI, USA) was activated for 65% of the total feed cycle. A 3-way solenoid valve was connected to a relay on the Hach® controller; this relay was activated when the DO in the reactor reached a user-defined setpoint. The solenoid would then stop air flow to the reactor and exhaust it outside the reactor until the DO dropped below the setpoint. The DO setpoint was initially set to 2 mg/L and gradually decreased in 0.1 to 0.2 mg/L increments until a minimum operating DO level was determined. Finally, temperature control was needed to maintain stable nitrification; therefore, an aquarium heater was installed in the reactor on day 150 and kept the reactor temperature at approximately 22^{o}C during cold weather. The shed that housed the pilot plant was fitted with a window air conditioning unit which allowed the reactor temperature to remain at approximately 22^{o}C during the hot summer months.

3.3.4 System feed

Feed for the pilot and laboratory-scale experiments was collected from the Virginia Tech dairy. Approximately 50 cows were detained on a concrete feeding floor for 8 hours. The manure was scraped off the floor and diluted at a 1:2 ratio (1 part manure to 2 parts total volume) with tap water. This mixture was run through a pilot-scale mechanical separator with 3.18 mm openings to remove solids. The liquid effluent was stored in several 5 gallon buckets at -20^{o}C until it was ready for use. Each bucket was thawed at room temperature (22-24^{o}C) for two days prior to use. Thawed feed was then diluted further at a 1:3 ratio with tap water for a final dilution of 1:6 (1 part manure to 6 parts total volume) before being fed into the fermenter for both the lab and pilot scale systems. Average feed characteristics are shown in Table 3-3.

Table 3-3. System feed characteristics.

Constituent	Values after feed dilution, 1:6 (standard deviation, number of samples)
TAN (mg/L-N)	150 (45)
Soluble COD (mg/L)	3,790 (450)
TSS (mg/L)	10,900 (2,500)
VSS (mg/L)	9,360 (2,370)

3.3.5 Denitrification experiments

Batch experiments were performed to determine denitrification rates for nitrite and nitrate as electron acceptor, as summarized in Table 3-4. Each batch experiment was performed in duplicate and used 1 L of N removal sludge collected on days 203 or 286. Batches were deoxygenated with N_2 gas to ensure anoxic conditions for the duration of the test. Each batch received supplemental electron acceptor at 100 mg/L as N (either NO_2^- or NO_3^-). An additional experiment was performed on day 203 that received NO_2^- plus NO_3^- at 100 mg/L N each. Sodium acetate (CH_3COONa) was spiked in excess of the stoichiometric requirement (2.0 and 4.9 COD:N for NO_2^- and NO_3^-, respectively) at concentrations reported in Table 3-4 to ensure that electron donor was not growth-rate limiting (Grady et al., 1999). The pH was continually maintained between 7.0 and 7.3 during each test. Samples were collected at 18 minute intervals and analyzed for NO_2^- using method 4500 NO_2^- B as described in Standard Methods (APHA, 1998), NO_3^- by ion chromatography (method 4110 as described in Standard Methods) using a Dionex DX300 with an AS40 autosampler (Dionex Corp., Sunnyvale, CA), VFA, TSS, and VSS as described in section 3.3.2. Linear regression was used to determine the specific denitritation, denitrification, and VFA consumption rates for each of the batch results.

Table 3-4. Denitrification batch experiment test conditions.

Batch test	NO_2^-, NO_3^-	Acetate
A,B[1]	100 mg/L NO_2^- - N	150 mg/L COD
C,D[1]	100 mg/L NO_3^- - N	370 mg/L COD
E,F	100 mg/L NO_2^- - N + 100 mg/L NO_3^- - N	520 mg/L COD

[1]Tests repeated on day 286

3.3.6 Tracking N species using a N balance

A stoichiometric N balance was performed on the system during the aerobic zone to define the approximate fate and tracking of N-species. The N balance included measured N species (gaseous and aqueous) and a theoretical estimate of the N required for biomass growth. Assuming a heterotrophic yield (Y_H) of 0.6 g biomass COD formed per g COD consumed, and assuming that substrate COD was in the form of typical domestic wastewater ($C_{10}H_{19}O_3N$, 1.99 g COD/g substrate), the following molar stoichiometric equation (normalized per mole of biomass ($C_5H_7O_2N$) formed) was determined for the oxidation of COD (Grady et al., 1999):

$$0.67\ C_{10}H_{19}O_3N + 3.33\ O_2 + 0.33\ HCO_3^- + 0.33\ NH_4^+ \rightarrow C_5H_7O_2N + 3.67\ H_2O + 2\ CO_2 \quad \text{Equation 3-1}$$

Equation 3-1 was used to calculate the approximate ratio of NH_4^+ consumed for heterotrophic biomass growth per unit SCOD consumed. Similarly, NH_4^+-N is used as the N source for autotrophic biomass ($C_5H_7O_2N$) growth according to the following equation assuming an autotrophic yield of 0.24 g biomass COD formed per g NH_4^+-N oxidized (Grady et al., 1999):

$$20.8\ NH_4^+ + NH_4^+\ \text{(cell synthesis)} + 15.8\ O_2 + 4\ CO_2 \rightarrow C_5H_7O_2N + 20.8\ NO_3^- + 19.8\ H_2O \quad \text{Equation 3-2}$$

To evaluate the contribution of autotrophic denitrification, an off gas analysis was performed for the N removal reactor on day 358 by inverting a funnel attached to a 10 L Tedlar gas bag beneath the liquid surface of the N removal reactor for approximately 30 seconds. The DO concentration at this point was held at 0.8 mg/L and according to the literature, the generation of gaseous byproducts by autotrophic denitrification is enhanced at microaerobic conditions such as those experienced in the N removal reactor at that point (Goreau et al., 1980). Samples were taken at times equal to 30% and 45% of the aerobic phase, and analyzed for N_2 and O_2 using a GOW-MAC gas chromatograph with a stainless steel column packed with molecular sieve 5 (Supelco) and TCD detector (isocratic, column = 35°C, injector = 70°C, detector = 70°C, TCD current = 200 mA, 100µL injection volume). Samples were also analyzed for N_2O using a Shimadzu GC14A with TCD detector, 6' long stainless steel column packed with Haysep D (program parameters were as follows: column temp: 40°C, isocratic, injector temp:70°C, detector temp:70°C, detector current: 175 mA, helium as carrier gas at 40 kPa.) and NO_x (NO_2 + NO) using a chemiluminescent NO_x analyzer (Ecophysics AG), Model CLD88Yl. NO_2 was calculated by subtracting the NO concentration from the NO_x total concentration.

3.4 Results and Discussion

3.4.1 Nearly complete TAN removal was observed in the N removal reactor

TAN removal values of close to 100% were observed in the N removal reactor for days 98-363 (Figure 3-2) and at DO concentrations as low as 0.8 mg/L.

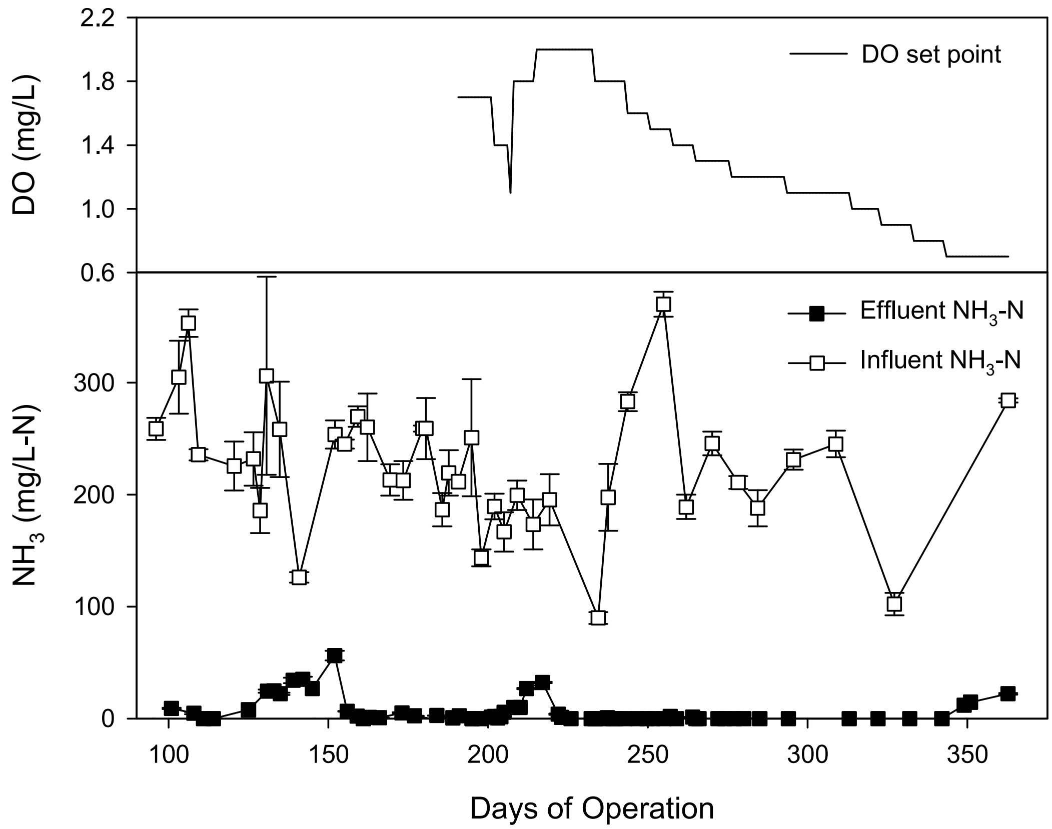

Figure 3-2. Influent TAN to the N removal reactor (fermenter effluent TAN) averaged 225 ± 59 mg/L-N TAN during days 98-363. The DO set point in the reactor was slowly decreased until effluent TAN began to accumulate.

The pilot plant aerobic zone was controlled at a DO of 2 mg/L from days 98-194 and 218-235. A typical cross cycle at those operating conditions is given in Figure 3-3. Approximately 100 percent of influent measured TAN was oxidized to NO_3^- during the aerobic zone which indicates substantial NOB activity. Therefore, on day 194 and again on day 236, the DO concentration in the aerobic zone was reduced to provide conditions where AOB would out-compete NOB for available oxygen and minimize the production of NO_3^-.

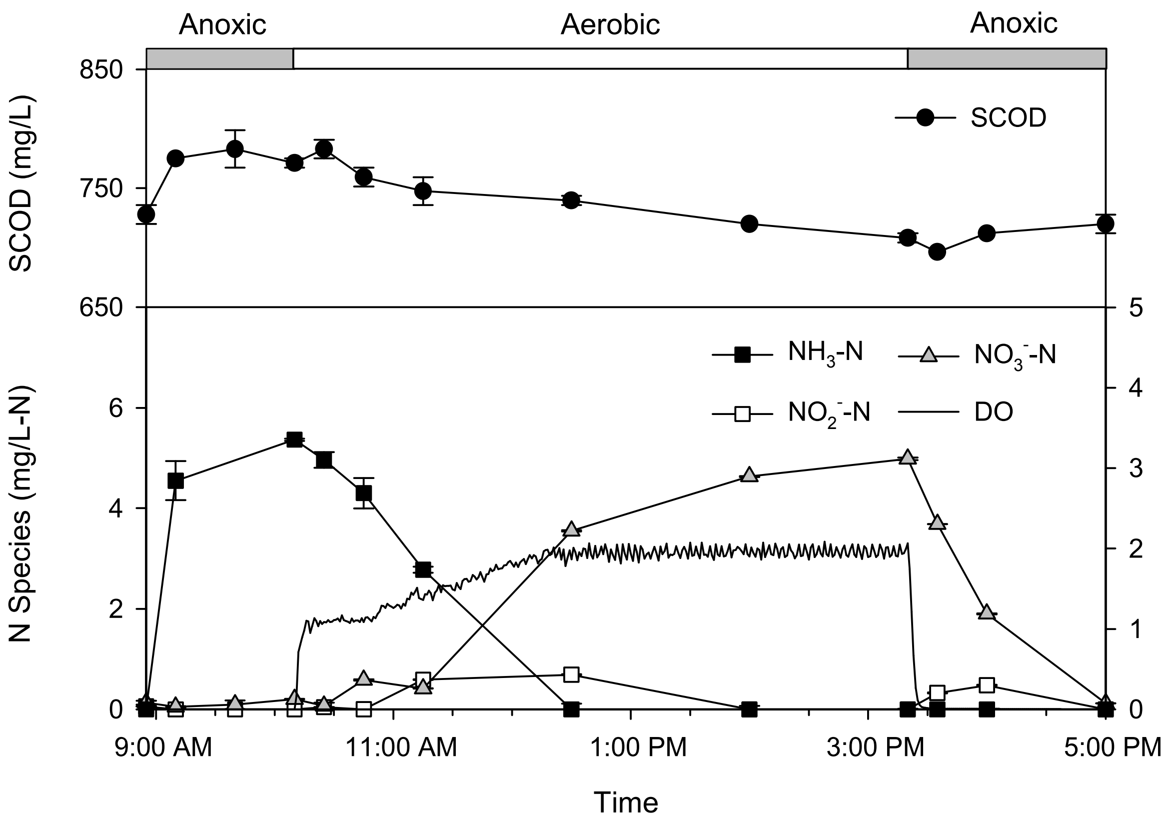

Figure 3-3. A typical cross cycle analysis performed on day 234 at a DO set point of 2.0 mg/L shows 5.4 mg/L TAN at the beginning of the aerobic cycle (10:10 AM). The TAN is oxidized to NO_2^- and NO_3^- during the aerobic zone. NO_3^- is denitrified in the final anoxic zone. System SRT = 10 days. Aerobic SRT = 6.5 days.

Total ammonia N oxidation was sensitive to sudden decreases in DO, as exhibited between days 204 and 210 when the DO set point was lowered from 1.7 to 1.4 mg/L on day 204 and again lowered from 1.4 to 1.1 mg/L on day 210. As a consequence, effluent TAN began to accumulate on days 205 through 210 and reached 32 mg/L-N TAN on day 210. The DO set point was increased to 2 mg/L and the system was allowed to stabilize until complete TAN removal (effluent TAN concentration below 0.05 mg/L-N) was achieved. The DO set point was subsequently decreased at a slower pace using 0.1 mg/L increments from 2.0 to 0.8 mg/L between days 236 and 357 (Figure 3-2) and cross cycle analyses (e.g., Figure 3-3) were completed for each DO set point. Approximately 100 percent TAN removal was observed during that period. However, when DO was set to 0.7 mg/L between days 358 and 363, insignificant NO_2^- and NO_3^- generation or TAN consumption was observed. Therefore, for the reactor and feed configuration used in this study, the minimum DO concentration that would allow for nitrification was 0.8 mg/L.

While the DO concentration in the aerobic zone is an important design parameter and was the focus of this research, the SRT required for N removal is also an important factor when designing BNR systems. The variable TAN concentrations in the system feed lead us to choose a sufficiently long aerobic SRT of 6.5 days to ensure stable nitrification. The aerobic SRT was calculated by multiplying the percent time that a complete feed cycle was aerobic (65%) times the total system SRT (10 days). N removal reactor cross cycle analyses yielded data from which the minimum aerobic time required for nitrification could be estimated. An average of 7.5 ± 5.5 mg/L of measured TAN was oxidized at an average observed rate of 7.5 ± 3.0 mg TAN day^{-1} $gVSS^{-1}$ from days 220 to 357 at DO concentrations from 2.0 to 0.8 mg/L. Using an average VSS concentration of 8,990 ± 1375 mg/L, an aerobic time of 2.7 hours (34% of the aerobic zone) would be required to remove all measured TAN. This corresponds to an aerobic SRT of 3.4 days and a safety factor of 1.9 (6.5 ÷ 3.4), which is reasonable for a nitrifying system (Grady et al., 1999). In comparison, successful nitritation systems exhibiting greater than 90% TAN removal have been operated at aerobic SRT values much lower than 3.4 days (Fux et al., 2006; van Kempen et al., 2001). The observation that our N removal reactor required much longer aerobic SRTs than is typical of nitritation reactors suggests (i) the presence of a nitrification inhibitor in the fermented dairy waste (ii) competition between heterotrophs and autotrophs that reduced the TAN oxidation rate or (iii) some combination of both factors.

Use of low dissolved oxygen concentrations to wash out NOBs, thus accumulating measured NO_2^- in the aerobic zone while minimizing the production of NO_3^-, was not accomplished with our system. In fact, no residual NO_2^- was measured at the end of the aerobic zone at all DO concentrations where nitrification occurred whereas NO_3^- was always present. This occurred because 100 % TAN removal was observed at all DO levels with the exception of 0.7 mg/L when AOB were inhibited as well as NOB. Researchers have found that when TAN is limiting, NOB activity is not impeded at DO concentrations as low as 0.07 mg/L (Sliekers et al., 2005) because AOB stop competing with NOB for available DO when TAN is not present. However, cycled aeration with frequent sequences of short aerobic phases followed by short anoxic phases has been successfully used to achieve N removal via NO_2^- when TAN is limiting (Hidaka et al., 2002).

NOB activity was delayed in activity due to competition with AOB and the lack of measured electron acceptor (NO_2^-) at the beginning of the aerobic zone. There was a period of time during each cross cycle where the net NO_2^- measured was orders of magnitude higher than the net NO_3^- measured. For DO concentrations between 1.4 and 0.8 mg/L, the maximum ratio of NO_2^-:NO_3^- on an N basis ranged from 6.9 to 3.0 and occurred after 1.5 aerobic hours (19% of the aerobic zone and an aerobic SRT of 1.9 days). An average of 4% of measured TAN removed was measured as NO_3^- during the time of the max NO_2^-:NO_3^--N ratio. This suggests that a 1.5 hour aerobic phase would be ideal for minimizing NOB activity. Furthermore, NO_2^- could be denitrified during an anoxic zone followed by another aerobic zone to remove residual TAN. Variable TAN content in the fermenter effluent and the original project objectives required the reactor configuration used in this project to achieve complete TAN removal. Nevertheless, the cross cycle data suggests that an aeration pattern consisting of several short aerobic (less than 1.5 aerobic hours) and subsequent anoxic periods could be used as a successful strategy in future research for minimizing the activity of NOB.

3.4.2 The fermenter produced VFA and other SCOD that can support denitrification

The laboratory and pilot-scale fermentation systems produced average VFA concentrations of 4,130 ± 235 mg/L and 2,930 ± 380 mg/L measured as COD, respectively, that were available as electron donor for denitrification (Table 3-5).

Table 3-5. Fermenter performance from days 98-363 of operation.

Constituent	Concentration (standard deviation of measurements)
sCOD (mg/L)	4,030 (390)
VFA (mg/L COD)[1]	
Acetic	1420 (330)
Proprionic	760 (240)
Isobutyric	90 (20)
Butyric	200 (110)
Isovaleric	70 (40)
Valeric	70 (70)
Isocaproic	5 (9)
Hexanoic	2 (10)
Heptanoic	40 (40)
TAN (mg/L)	230 (60)
TSS (mg/L)	14,100 (2,450)
VSS (mg/L)	11,800 (1,830)

[1]VFA COD equivalents calculated using the ratio of mass of theoretical oxygen demand per mass VFA as described by Grady et al. (1999)

Samples were taken and analyzed for VFA and SCOD concentrations in each cross cycle tested, but the N removal sample matrix caused an unknown interference with the VFA analysis method at the low VFA concentrations analyzed. This caused inaccuracies in the cross cycle VFA data, but did not effect the higher concentrations measured in the fermenter effluent. Therefore, a theoretical VFA added to the N removal reactor during each feed cycle was calculated using an average fermenter effluent VFA concentration and dilution effects (5 L fermenter effluent into 150 L N removal reactor) and was found to be 89 ± 11 mg/L VFA as COD. This accounted for 65% of the total added SCOD (135 ± 13 mg/L, 1.5 μm glass microfiber filter, calculated using fermenter effluent data) during days 98-363. Additionally, the pilot scale fermenter produced SCOD and TAN at concentrations that were 6% and 53%, respectively, higher than the values measured in the unfermented feed (Tables 3-3 and 3-5).

3.4.3 Denitrification in the N removal reactor was supported by VFA and unidentified SCOD

The fact that both electron donor and TAN were present in the fermenter effluent and produced in excess of the unfermented feed motivated the aeration pattern of anoxic-aerobic-anoxic, used in the N removal reactor. Total ammonia N could be oxidized to NO_2^- and NO_3^- in the aerobic zone and then subsequently denitrified in the anoxic zone or anoxic regions in the aerobic zone fueled by the electron donor produced through anaerobic fermentation. However, other non-VFA SCOD may have also been used as an electron donor for denitrification. This is most probable in the second anoxic zone where the VFA and other readily biodegradable SCOD were most likely consumed during the aerobic zone.

To investigate the nature of the SCOD used in the final anoxic zone for denitrification, a maximum substrate removal rate, $\hat{q}$ (Grady et al., 1999), was calculated to ultimately determine the theoretical time required to remove all VFA during the aerobic zone and is defined by:

$$\hat{q} = \frac{\hat{\mu}}{Y_H} \qquad \text{Equation 3-3}$$

where:

Table 3-6. Equation 3-3 variables and results.

Description	Variable	Value
VFA at beginning of cycle[a]		89
Heterotrophic Yield[b]	Y_H	0.6 g COD per g COD
Maximum specific growth rate[b]	$\hat{\mu}$	6.0 day^{-1}
VFA removal rate[c]	$\hat{q}$	10 g VFA COD per g biomass COD per day
Average VSS[a] (assuming 1.42 mg COD/mg VSS[b]) in N removal reactor		14,500 mg/L COD
Assumed active heterotrophic biomass fraction of VSS[d] (determined as an assumed worst case)		1%
Active heterotrophic biomass COD[c]		145 mg/L
Time required for complete VFA removal[c]		1.5 hours (29% of total aerobic zone)

[a]Calculated value based on actual measured data
[b]Assumed variables and constants (Grady et al., 1999)
[c]Calculated value
[d]Value based on an assumed worst case scenario

As a worst case scenario, the active heterotrophic biomass concentration was assumed to be 1%. Realistically, the active biomass fraction of VSS COD would be greater than 1% (Grady et al., 1999) and would result in a higher VFA removal rate and lower time required for complete VFA removal. Nevertheless, using the assumed worst case value, only 1.5 aerobic hours (29% of the aerobic zone) would be required to remove all VFA COD. Additionally, 80% ± 17% of measured SCOD removal, (73 ± 40 mg COD/L out of a total 90 ± 41 mg/L COD removed during the aerobic zone) occurred during the first 40% (2 hr, 5 min) of the aerobic time in each cross cycle tested. This suggests that the readily biodegradable COD (most likely VFA) was consumed during that time frame and was not available as a carbon source for the denitrification that occurred during the second anoxic zone. Nevertheless, an average of 5.3 ± 2 mg/L NO_3^--N was reduced at a rate of 13 ± 3.4 mg NO_3^--N day^{-1} $gVSS^{-1}$ during the second anoxic zone of the cross cycles tested. This confirms that heterotrophic denitrification was not entirely carbon source limited in the second anoxic zone even though the readily biodegradable VFA produced by the fermenter was probably not present at that point.

Denitrification rates found in batch experiments where electron donor in the form of acetic acid was spiked in excess also support our conclusion that VFAs were not available as an electron donor in the final anoxic zone. The average NO_3^- reduction rate (50 ± 15 mg NO_3^--N day^{-1} $gVSS^{-1}$) in the denitrification experiments was approximately 4 times the observed NO_3^- reduction rate in the final anoxic zone of the cross cycles. Therefore, VFAs used as electron donor for denitrification do have kinetic advantages, but slowly biodegradable COD consumed in the final anoxic zone was sufficient given the reactor configurations tested.

Table 3-7. Denitrification rates from batch assays using N removal biomass: value (standard deviation).

Experiment (spiked with NO_2^-, NO_3^-)	NO_2^- consumption rate (mg N/day/g VSS)	NO_3^- consumption rate (mg N/day/g VSS)	Calculated NO_2^- consumption rate (mg N/day/g VSS)	Acetate consumption rate (g COD/g N reduced)
100 mg/L NO_2^-	18 (4)	--	--	5.3 (1.0)
100 mg/L NO_3^-	- 39 (15)[1]	50 (15)	10 (3)	6.4 (1.6)

Test results averaged from two replicates each from both days 203 and 286
[1]Negative value indicates NO_2^- accumulation

Denitrification test results have also shown clear kinetic advantages for achieving N removal from NO_2^- only. When NO_3^- and NO_2^- are both present, competition exists between NO_2^- reductase and NO_3^- reductase and impeded NO_2^- removal rates compared to those in the absence of NO_3^-. Nitrite was found to accumulate in batches spiked with 100 mg/L NO_3^--N only which has also been reported by researchers performing denitrification experiments where acetate was used as a carbon source for denitrification (van Rijn et al., 1996). For the case where NO_2^- was found to accumulate, a theoretical NO_2^--N reduction rate was calculated by subtracting the rate or NO_2^--N that accumulated from the rate of NO_3^- that was consumed (Table 3-7) and was found to be 55% of the NO_2^--N consumption rate when NO_3^- was not present. Additionally, the acetate COD consumed during N reduction from NO_3^- (Table 3-7) was found to be 21% greater compared to the reduction of NO_2^- in the absence of NO_3^-. This is less than the electron donor savings when denitrifying via NO_2^-, stoichiometrically determined to be 40% based on and electron balance (reduction of NO_2^- and NO_3^- to $N_{2(g)}$ requires 3 mol e- per mol e^- donor, and 5 mol e^- per mol e- donor, respectively. This suggests that other SCOD may have been used that was not accounted for in the VFA measurements.

3.4.4 Simultaneous nitrification-denitrification (SND) was most likely occurring in the N removal reactor at low DO concentrations

Based on a reasonable N balance and COD:N ratios available during the aerobic zone, it is probable that SND was occurring at low levels of dissolved oxygen. The percent of total removed TAN accounted for by the net production of NO_2^- during the aerobic zone initially increased as the DO set point was decreased and reached a maximum of 42% at a DO set point of 1.3 mg/L (Figure 3-4). This suggests that the activity of AOB increased relative to the activity of NOB with each decrease in DO, presumably due to the competitive growth advantage that AOB have relative to NOB at decreasing DO concentrations. However, the percent of total removed TAN measured as NO_2^- peaked at a DO of 1.3 mg/L and began to decrease as the DO was lowered below 1.3 mg/L. Additionally, the maximum percent of removed TAN measured as NO_3^- during the aerobic zone was actually greater than 100% at higher DO set point levels (1.5 – 2.0 mg/L). Although TKN was not routinely measured, periodic TKN measurements indicated that the TAN was approximately 65% of the TKN. Therefore, the higher production of NO_3^- can be explained by ammonification of organic N to TAN and subsequent oxidation to NO_3^- during the aerobic zone. The percent of removed TAN recovered as measured oxidized N species at the end of the aerobic zone was approximately 100% at DO set point concentrations of 1.3 to 1.5 mg/L and then decreased as the DO was lowered below 1.3 mg/L (Figure 3-4).

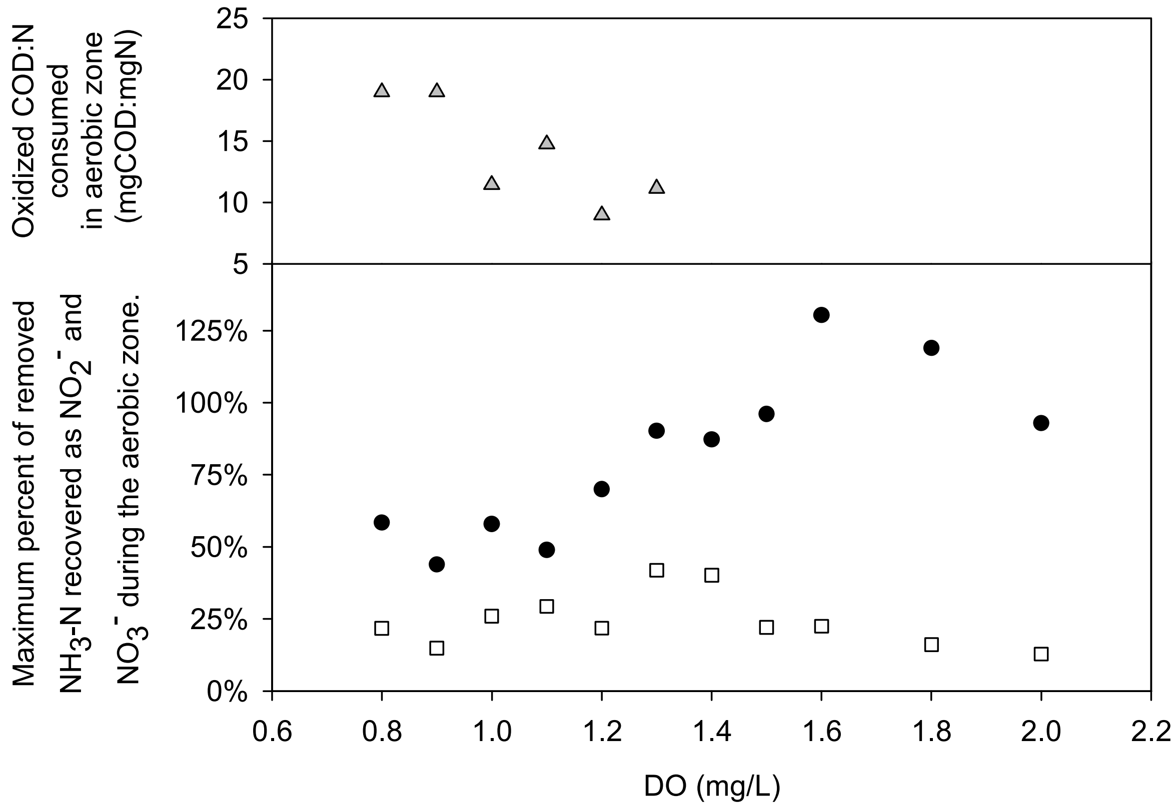

Figure 3-4. The maximum percent of TAN removed that was measured as NO_2^- during the aerobic phase (□) reached a maximum of 42% at a DO set point of 1.3 mg/L. Likewise, the percent of removed TAN recovered as measured NO_3^- during the aerobic zone (●) dropped below 95% at DO levels below 1.3 mg/L. COD removed:TAN removed (△) is plotted for DO concentrations that exhibited SND potential based on an N balance.

In order to confirm the possible presence of SND, a N balance was completed that incorporated all net measured N-species and estimated N used for cell growth using equations 3-1 and 3-2 during the aerobic zone. These values were calculated using the stoichiometric ratios of 0.018 mg N assimilated /mg COD consumed and 0.048 mg N assimilated /mg NH_4^+ oxidized for heterotrophic and autotrophic species, respectively (Appendix Equations B-2 and B-3).

The production of gaseous N products, was evaluated on day 358 when the DO was set to 0.8 mg/L during the aerobic zone. Due to the instrument sensitivity and the low mass of N entering the aerobic zone, the N_2 produced by denitrification was too small to be differentiated from ambient N_2. As a result, the contribution of gaseous N_2 from denitrification to the N balance was not quantifiable. The production of N_2O, a product of AOB denitrification was also below detection. Therefore, the contribution of autotrophic denitrification was determined to be insignificant. Littleton et al. (2003) came to a similar conclusion that autotrophic denitrification made a negligible contribution to overall N removal after running several batch experiments on mixed liquor taken from plants that exhibited significant SND. Finally, the concentration of gaseous NO_x (NO_2 + NO) appeared be greater in the reactor compared to the laboratory air but represented less than 0.01% (0.045 mg N hr^{-1} NO_x compared to 323 mg N hr^{-1}) of the influent TAN. Nevertheless, an N balance was completed by subtracting the initial N at the beginning of the aerobic zone of the cross cycle (TAN) from the final N at the end of the aerobic zone (both measured oxidized N species, and calculated N present in biomasses) (Table 3-8) to calculate a net N change during the aerobic zone (Figure 3-5).

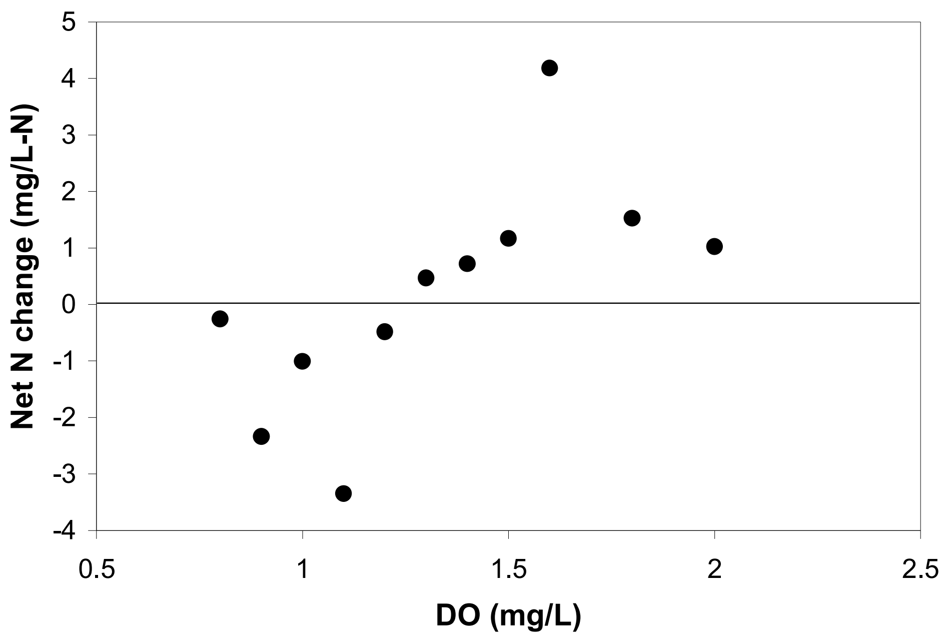

Figure 3-5. The net change in N during the aerobic zone (●) at each DO concentration.

Table 3-8. Nitrogen balance performed for each cross cycle at various DO concentrations.

DO (mg/L)	Initial measured TAN concentration at the beginning of the aerobic zone (mg/L-N)	mg/L N calculated for heterotrophic biomass growth based on SCOD removal	mg/L N calculated for autotrophic biomass growth based on TAN removed	Final measured N at the end of the aerobic phase: (NO_3^-, mg/L-N)	Net N change in the aerobic zone (final N – initial N)	COD removed: TAN removed during the aerobic zone
2.0	5.37	1.20	0.20	4.99	1.02	
1.8	6.45	0.00	0.31	7.67	1.53	
1.6	8.04	1.76	0.30	10.17	4.18	
1.5	11.98	1.12	0.52	11.51	1.17	
1.4	8.85	1.57	0.35	7.66	0.72	
1.3	8.47	0.97	0.36	7.60	0.47	
1.2	6.34	1.24	0.24	4.37	-0.49	11
1.1	9.78	1.53	0.40	4.50	-3.35	9
1.0	7.06	1.82	0.25	3.98	-1.01	15
0.9	7.16	1.43	0.27	3.11	-2.34	11
0.8	4.14	1.38	0.13	2.37	-0.26	19

Positive changes in net N for the N balance were found for DO concentrations 2.0-1.3 and indicate that organic N (not included in the N balance) may have contributed to the overall measured and calculated N species in the aerobic phase. On the other hand, negative changes in the net N change were found for DO concentrations between 1.2 and 0.8 mg/L and confirm that net soluble N was lost from the system at low DO concentrations. While organic N may have been oxidized at these levels, these results suggest that heterotrophic denitrification was most likely occurring as well, although it was not possible to resolve biologically-produced N_2 from background ambient concentrations. Furthermore, the COD removed:TAN removed at DO concentrations where negative net N changes occurred ranged from 9-19 mg COD:mg N (worst case scenario where all influent TAN was assumed to be subject to SND) which is higher than the minimum required COD:N ratio of 4.9 (Grady et al., 1999) and would therefore be sufficient to support denitrification in the aerobic zone.

The negative change in net N at DO levels 0.8-1.2 suggests a phenomenon known as simultaneous nitrification–denitrification (SND) wherein micro-aerobic zones in a reactor allow for autotrophic nitrification and heterotrophic denitrification to occur simultaneously in the same reactor. The mechanisms that allow for SND to occur are related to the bioreactor macroenvironment such as incomplete mixing and air diffusion limitations, the presence of anoxic and micro-aerobic zones within the flocs, and novel microorganisms such as autotrophic denitrifiers under oxygen limited conditions (Daigger and Littleton, 2000). The average TSS concentration in the N removal reactor was 11,740 ± 1,750 mg/L which was an order of magnitude larger than the range that was tested by Daigger and Littleton (2000) in several plants that exhibited SND (2,150-4,000 mg/L). Researchers have found a direct correlation between floc size and the occurrence of SND (Munch et al., 1996). While the floc size was not measured for this system, the high solids concentration suggests that the conditions were favorable for large floc sizes. The results obtained from the cross cycle analyses and N balance as well as the favorable conditions measured in the N removal reactor show that SND was likely occurring and was most clearly seen at DO concentrations below 1.3 mg/L.

3.5 Conclusions

As a result of the findings from this research, the following conclusions were drawn:

- N removal was accomplished at DO concentrations at or above 0.8 mg/L using this set-up. However, the goal of achieving N removal via NO_2^- only was not achieved because 100% TAN removal was observed which eliminated the competition between AOB and NOB and allowed the net oxidation of NO_2^- to NO_3^- at all DO concentrations where nitrification was occurring.

- VFAs produced through the anaerobic fermentation of dairy waste can be a viable source of electron donor for heterotrophic denitrification but sufficient non-VFA sCOD was present in fermented dairy manure to support complete denitrification at the cost of slower denitrification rates.

- Based on a reasonable N balance and COD:N ratios available during the aerobic zone, it is probable that SND was occurring, and was most apparent at and below a DO of 1.3 mg/L at an average TSS concentration of 11,740 ± 1,750 mg/L.

Reactor configurations that enhance the presence of SND could be used as a successful N removal strategy where both electron donor and TAN are present in the system feed and would be used to fuel nitrification and denitrification simultaneously.

3.6 Acknowledgments

Funding for this project was provided by the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET). Funding for the facility that housed this project was provided by the Virginia Agricultural Council. The authors would like to thank Jody Smiley, Julie Petruska, Barry Musick, and Monika Mohs for their support and assistance in the laboratories. The authors would also like to thank Dale Gardner of the Virginia State Dairyman's Association.

3.7 References

Amon, B., Kryvoruchko, V., Amon, T. and Zechmeister-Boltenstern, S. (2006). Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agriculture, Ecosystems and Environment*, **112**(2-3), 153-162.

Anthonisen, A. C., Loehr, R. C., Prakasam, T. B. S. and Srinath, E. G. (1976). Inhibition of nitrification by ammonia and nitrous acid. *Journal Water Pollution Control Federation*, **48**(5), 835-852.

APHA. (1998). *Standard Methods for the Examination of Water and Wastewater. 21st ed*. American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF).

Beck, J. L., Love, N. G., Gilmore, K. R., Knowlton, K. F. and Ogejo, J. A. (2007). Nitrification inhibition by fermented dairy manure: Identifying the presence of an inhibitor and its effect on nitrifying kinetic parameters. *In preparation for submission to Bioresource Technology*.

Daigger, G. T. and Littleton, H. X. (2000). Characterization of simultaneous nutrient removal in staged, closed-loop bioreactors. *Water Environment Research*, **72**, 330-339.

Fux, C., Velten, S., Carozzi, V., Solley, D. and Keller, J. (2006). Efficient and stable nitritation and denitritation of ammonium-rich sludge dewatering liquor using an SBR with continuous loading. *Water Research*, **40**(14), 2765-2775.

Grady, L. C., Daigger, G. T. and Lim, H. C. (1999). *Biological Wastewater Treatment*. Marcel Dekker, Inc., New York, NY.

Goreau, T. J., Kaplan, W. A., Wofsy, S. C., McElroy, M. B., Valois, F. W. and Watson, S. W. (1980). Production of NO_2^- and N_2O by nitrifying bacteria at reduced concentrations of oxygen. *Applied Environmental Microbiology*, **40**(3), 526-532.

Hellinga, C., Schellen, A. A. J. C., Mulder, J. W., van Loosdrecht, M. C. M. and Heijnen, J. J. (1998). The SHARON process: An innovative method for nitrogen removal from ammonium-rich waste water. *Water Science and Technology*, **37**(9), 135-142.

Herbst, R. (2002). The State of the Chesapeake Bay. Chesapeake Bay Program of the U.S. Environmental Protection Agency. 903-R-02-002.

Hidaka, T., Yamada, H., Kawamura, M. and Tsuno, H. (2002). Effect of dissolved oxygen conditions on nitrogen removal in continuously fed intermittent-aeration process with two tanks. *Water Science and Technology*, **45**(12), 181-188.

Khin, T. and Annachhatre, A. P. (2004). Novel microbial nitrogen removal processes. *Biotechnology Advances*, **22**(7), 519-532.

Knowlton, K. F., Love, N. G. and Parsons, C. M. (2005). Dietary phosphorus effects on characteristics of mechanically separated dairy manure. *Transactions of the ASAE*, **48**(3), 1253-1258.

Littleton, H. X., Daigger, G. T., Strom, P. F. and Cowan, R. A. (2003). Simultaneous biological nutrient removal: evaluation of autotrophic denitrification, heterotrophic nitrification, and biological phosphorus removal in full-scale systems. *Water Environment Research*, **75**(2), 138-150.

Munch, E. V., Lant, P. and Keller, J. (1996). Simultaneous nitrification and denitrification in bench-scale sequencing batch reactors. *Water Research*, **30**(2), 277-284.

MWPS. (1993). *Livestock waste facilities handbook. 3rd ed*. MidWest Plan Service, Iowa State University, Ames, Iowa.

Ruiz, G., Jeison, D. and Chamy, R. (2003). Nitrification with high nitrite accumulation for the treatment of wastewater with high ammonia concentration. *Water Research*, **37**(6), 1371-1377.

Ruiz, G., Jeison, D., Rubilar, O., Ciudad, G. and Chamy, R. (2006). Nitrification-denitrification via nitrite accumulation for nitrogen removal from wastewaters. *Bioresource Technology*, **97**(2), 330-335.

Sliekers, A. O., Haaijer, S. C. M., Stafsnes, M. H., Gijs Kuenen, J. and Jetten, M. S. M. (2005). Competition and coexistence of aerobic ammonium- and nitrite-oxidizing bacteria at low oxygen concentrations. *Applied Microbiology and Biotechnology*, **68**(6), 808-817.

Tallec, G., Garnier, J., Billen, G. and Gousailles, M. (2006). Nitrous oxide emissions from secondary activated sludge in nitrifying conditions of urban wastewater treatment plants: Effect of oxygenation level. *Water Research*, **40**(15), 2972-2980.

Tchobanoglous, G., Burton, F. L. and Stensel, H. D. (2003). *Wastewater Engineering: Treatment and Reuse*. *4th ed*. Metcalf and Eddy, McGraw-Hill, Boston.

Turk, O. and Mavinic, D. S. (1989). Maintaining nitrite build-up in a system acclimated to free ammonia. *Water Research*, **23**(11), 1383-1388.

Van Horn, H. H., Wilkie, A. C., Powers, W. J. and Nordstedt, R. A. (1994). Components of dairy manure management systems. *Journal of Dairy Science*, **77**, 2008-2030.

van Kempen, R., Mulder, J. W., Uijterllnde, C. A. and van Loosdrecht, M. C. M. (2001). Overview: full scale experience of the SHARON process for treatment of rejection water of digested sludge dewatering. *Water Science and Technology*, **44**(1), 145-152.

van Rijn, J., Tal, Y. and Barak, Y. (1996). Influence of volatile fatty acids on nitrite accumulation by a *Pseudomonas stutzeri* strain isolated from a denitrifying fluidized bed reactor. *Applied and Environmental Microbiology*, **62**(7), 2615-2620.

4 NITRIFICATION INHIBITION BY FERMENTED DAIRY MANURE: IDENTIFYING THE PRESENCE OF AN INHIBITOR AND ITS EFFECT ON AOB KINETIC PARAMETERS

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4.1 Abstract

A series of nitrite generation rate batch experiments confirmed the presence of an unknown nitrification inhibitor in fermented dairy manure. Nitrifying activity was shown to increase when nitrifying biomass samples were exposed to decreasing concentrations of fermenter supernatant, and reached a maximum of approximately 4 mg N $gVSS^{-1}$ day^{-1} at dilutions above 1:5 (1 part fermenter supernatant and 4 parts water). Furthermore, TAN removal rates exhibited in a pilot scale nitrifying reactor were approximately half of those determined by BioWin®, a biological modeling software package. A kinetic and stoichiometric sensitivity analysis was performed with BioWin® and showed that effluent TAN was most sensitive to changes in the AOB maximum specific growth rate and the substrate half-saturation coefficient. Nitrifying inhibition terms for competitive, non-competitive, uncompetitive, and mixed inhibition were calibrated in a BioWin® model such that the model results closely resembled field collected data. Furthermore, the default hydrolysis rate was found to be too low when applied to dairy waste. All inhibition mechanisms could be adjusted to fit the field data with reasonable accuracy once the hydrolysis rate was reduced, but the uninhibited growth rate still did not fit,

indicating some kind of nitrification inhibition was occurring. Without further experiments, the nature of the inhibitor could not be elucidated.

Keywords

Nitrification inhibition, fermented dairy manure, NGR, dairy manure, nitrification, inhibition mechanisms

4.2 Introduction

Excess bioavailable nitrogen (N) in the form of total ammonia nitrogen (TAN) from agriculture, specifically animal feeding operations (AFOs), can contribute to eutrophication and the degradation of the watersheds associated with the facilities. Nitrogen removal techniques need to be implemented that optimize the bioavailability of reduced N in manure, a valuable asset for crop fertilization, while minimizing the production of excess TAN that can leech into surrounding waterways or volatilize into the atmosphere. One such N removal technique couples nitrification (aerobic oxidation of TAN to NO_2^- and/or NO_3^-) with denitrification (reduction of NO_2^- and NO_3^- to N_2 gas), and has been used for decades in wastewater treatment plants (WWTPs) that process domestic sewage. However, manure waste from AFOs such as dairy operations contains nutrients, organics, solids, and other constituents at concentrations that are orders of magnitude higher than municipal wastewater. For example, COD and TAN concentrations in the liquid effluent from solids-separated dairy manure are 87 and 35 times that of municipal wastewater, respectively (Knowlton et al., 2005; Reynolds and Richards, 1996; Tchobanoglous et al., 2003). Therefore, technologies developed for domestic wastewater treatment may require modification before being applied as manure treatment technologies for animal agriculture.

Nitrification is accomplished in a two-step process by two distinct groups of bacteria, ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB). This research focuses on the results obtained from a pilot-scale N removal system where N was removed from fermented dairy manure that was found to inhibit TAN oxidation. The enzyme responsible for TAN oxidation, ammonia monooxygenase (AMO) is capable of oxidizing a wide variety of substrates which can create competition for the active site resulting in nitrification inhibition (Hockenbury and Grady, 1977). Specifically, AOB and NOB are known to be sensitive to and inhibited by free ammonia (NH_3) and nitrous acid (HNO_2) (Anthonisen et al., 1976), free-hydroxylamine (NH_2OH) (Hao and Chen, 1994), and a wide range of organic compounds and acids (Eilersen et al., 1994) as well as heavy metals (Kelly et al., 2004). Although the specific identity of the inhibitor is often unknown, the mechanism as well as the inhibition constants responsible for the mechanism can often be determined using experimental data. Inhibitors can act according to several different mechanisms including competitive, non-competitive, uncompetitive, or mixed inhibition as defined by Grady et al. (1999) and Rawn (1989).

Competitive inhibition increases the observed half-saturation constant of AOB ($K_{NH_4^+}$) in the Monod equation for microbial growth, μ_{AOB}, (Equation 4-1) such that a new $K_{NH_4^+}$, termed $K_{NH_4^+,I}$ (Equation 4-2), must be determined on a mechanistic basis. However, the $\hat{\mu}_{AOB}$ is not directly affected by the inhibitory compound (Grady et al., 1999).

$$\mu_{AOB} = \hat{\mu}_{AOB} \frac{S_{NH_4^+}}{K_{NH_4^+,I} + S_{NH_4^+}} \qquad \text{Equation 4-1}$$

where

$\hat{\mu}_{AOB}$ = maximum specific growth rate of AOB, day^{-1}

$S_{NH_4^+}$ = NH_4^+ concentration, mg/L-N

$K_{NH_4^+,I}$ = apparent ammonia half-saturation constant (mg/L-N) in the presence of an inhibitor and is represented by:

$$K_{NH_4^+,I} = K_{NH_4^+}\left(1 + \frac{S_I}{K_I}\right) \qquad \text{Equation 4-2}$$

where:

S_I = concentration of the inhibitory compound, and

K_I = inhibition constant

Alternatively, the non-competitive inhibition mechanistic description is modeled as a direct decrease in the observed $\hat{\mu}_{AOB}$ of AOB through the following relationship (Grady et al., 1999; Nowak et al., 1995):

$$\mu_{AOB} = \hat{\mu}_{AOB,I} \frac{S_{NH_4^+}}{K_{NH_4^+} + S_{NH_4^+}} \qquad \text{Equation 4-3}$$

Where:

$\hat{\mu}_{AOB,I}$ = apparent maximum specific growth rate of AOB in the presence of an inhibitor and is represented by:

$$\hat{\mu}_{AOB,I} = \hat{\mu}_{AOB} \frac{K_I}{K_I + S_I} \qquad \text{Equation 4-4}$$

Finally, two separate combinations of both competitive and non-competitive inhibition, termed mixed and uncompetitive inhibition, can occur. Mixed inhibition is modeled by replacing both $K_{NH_4^+}$ and $\hat{\mu}_{AOB}$, with $K_{NH_4^+,I}$ and $\hat{\mu}_{AOB,I}$ as determined by Equations 4-2 and 4-4, respectively. This has the effect of increasing and decreasing the uninhibited $K_{NH_4^+}$ and $\hat{\mu}_{AOB}$, respectively, in the Monod equation (Table 4-1) Conversely, uncompetitive inhibition decreases both $\hat{\mu}_{AOB}$ and $K_{NH_4^+}$, by replacing them with the terms $\hat{\mu}_{AOB,I}$ and $K_{NH_4^+,uncomp.}$ as defined by Equations 4-4 and 4-5, respectively.

$$K_{NH_4^+,uncomp.} = K_{NH_4^+}\left(1 + \frac{S_I}{K_I}\right)^{-1} \qquad \text{Equation 4-5}$$

Table 4-1: Inhibition mechanisms and their effects on the uninhibited values of $\hat{\mu}_{AOB}$ and $K_{NH_4^+}$.

Inhibition mechanism	Effect on $\hat{\mu}_{AOB}$	Effect on $K_{NH_4^+}$
Competitive	None	Increase
Noncompetitive	Decrease	None
Mixed	Decrease	Increase
Uncompetitive	Decrease	Decrease

(Grady et al., 1999)

In recent years, software simulation packages that incorporate pseudo-kinetic models coupled with flow models have been used to design and optimize the operation of biological treatment systems (Jones et al., 2005). However, to correctly use these simulation packages, the influent wastewater must be correctly characterized to adequately calibrate the model. Furthermore, biological inhibitors present in the waste can yield field results that are largely different than predicted using non-inhibition models. If an inhibitor is present, the equations above make it clear that the nature of the inhibitors' mechanism of action must be determined before software models can be calibrated correctly.

A recent study or N removal from dairy waste showed possible evidence of nitrification inhibition in fermented dairy manure (Beck et al., 2007). The objective of this study was to determine the presence of a nitrification inhibitor in dairy waste and characterize its mechanism. Additionally, modeling simulations were conducted to adequately calibrate a BioWin® model such that the modeling results closely resembled field collected data and accounted for the inhibitor detected in the system influent.

4.3 Methods

4.3.1 Pilot scale nitrogen removal system

A two step N removal treatment system designed to treat solids-separated dairy manure was constructed and operated as a sequencing batch reactor at the Virginia Tech dairy facility. The system consisted of an upstream fermentation reactor that provided both bioavailable N as TAN and volatile fatty acids (VFAs) as electron donor for denitrification. Effluent from the fermentation system flowed by gravity into an N removal reactor (N removal) where TAN removal was accomplished through a nitrification/denitrification process by cyclic aeration patterns to create a series of aerobic and anoxic zones in the same reactor (Beck et al., 2007).

4.3.2 Nitrite generation rate (NGR) inhibition experiments

System performance data and preliminary respirometric SOUR assays indicated that nitrification inhibition might be occurring (Appendix Sections A.3 and C.1). However, SOUR experiments conducted in our laboratory have shown that chemical nitrification inhibitors are problematic when performing nitrification inhibition assays. Therefore, to confirm the inhibition patterns witnessed in the field and with preliminary SOUR assays, nitrite generation rate (NGR) experiments were used to test the nitrifying activity of AOB when exposed to various concentrations on fermenter supernatant. Sodium azide (NaN_3) was used to inhibit the activity of NOB (Kelly et al., 2004).

Previous experiments conducted by researchers in our laboratory have suggested that the optimum concentration of NaN_3 needed for NOB inhibition can vary depending on the mixed liquor being tested (Kelly et al., 2004). Therefore, a NaN_3 optimization experiment was conducted using varying concentrations of NaN_3 applied to batches containing identical amounts of nitrifying sludge, TAN, and alkalinity. NGRs were determined using linear regression. The concentration of NaN_3 that yielded the maximum NGR was found to be 200 μM and was used for the inhibition test (Appendix Section C.2.1).

On day 342, N removal sludge was taken from the reactor and separated into 50 mL aliquots. The aliquots were then centrifuged, pelleted and resuspended in various dilutions of fermenter supernatant: dilutions of 1:1 (concentrated), 1:2, 1:5, and 1:10 (1:x dilution defined as 1 part fermenter supernatant to x total parts using tap water as the dilution liquid) in biological duplicate reactors as well as a control that did not receive any fermenter effluent. Finally, each batch was spiked with approximately 75 mg/L

NH_4Cl-N and 200 μM NaN_3. The sludge was then kept in a controlled environment (pH: 7.0-7.3, DO > 6 mg/L, temp: 23°C, completely mixed) during incubation for one hour. Samples were taken at times 0, 15, 30, 45 and 60 minutes and analyzed for NO_2^- per method 4500 NO_2^- B as described in standard methods (APHA, 1998).

4.3.3 BioWin® model sensitivity analysis and modeling

BioWin® version 3.0 (Envirosim Associates, Ltd.) is a computer modeling program that allows the user to simulate complex biological systems so that key configuration values and system performance can be evaluated. Kinetic and stoichiometric parameters for AOB can be adjusted based on field measured data. As described previously, field and lab results suggested that a nitrification inhibitor may be present in dairy waste and may affect the default parameters in BioWin® for nitrifying bacteria. Therefore, a sensitivity analysis was conducted to determine which parameters for AOB are the most sensitive to change such that they could be adjusted to in an attempt to calibrate the model.

Several methods have been developed to determine a model's output sensitivity to changes in various model parameters. The simplest method is known as the One At a Time method (OAT) where parameters are changed in equal percentage increments and the output sensitivity is subsequently calculated (Campolongo and Saltelli, 1997).
The model's sensitivity to each parameter is evaluated by dividing the percentage change in output value by the percentage change in parameter value according to:

$$S_R = \frac{(O - O_b)}{(P - P_b)} \frac{P_b}{O_b} \qquad \text{Equation 4-6}$$

where: O = output value, P = parameter value, b = subscript indicating baseline value.

A standard operating condition used with the pilot scale system was established as the base case in BioWin®. That operating condition was: feed for 2 min at the beginning of a 1 hr 10 min anoxic phase, aerobic for 5 hr 10 min, and pump mixed liquor effluent for the last 2 minutes of a 1 hr 40 min anoxic phase. The system feed was characterized with both measured data and calculated estimates to mimic the actual pilot scale system. Two baseline scenarios, defined by DO, were established for the sensitivity analysis. Baseline

1 (BL_1) had a DO of 0.8 mg/L during the aerobic zone to mimic the minimum DO required for TAN oxidation with the pilot scale system (Beck et al., 2007). Baseline 2 (BL_2) had a DO of 2 mg/L to mimic a complete nitrifying scenario. A subset of parameters, identified in Table 4-2, was adjusted in increments of: -50, -30, -10, 10, 30 and 50 percent of the default value given in BioWin. Effluent TAN, NO_2^-, and NO_3^- were recorded for each parameter change. Dynamic model simulations were run for 80 days in order to achieve steady state based on negligible changes in effluent TAN, NO_2^-, NO_3^-, sCOD, and VFA concentrations at this value.

Table 4-2: Key kinetic and stoichiometric parameters for AOB were adjusted for the BioWin® sensitivity analysis.

	Percent Change						
Biowin Parameter	-50	-30	-10	(default)	10	30	50
Yield (mg COD / mg N)	0.075	0.105	0.135	0.15	0.165	0.195	0.225
Substrate (NH_4^+) half saturation constant (mg N/L)	0.35	0.49	0.63	0.7	0.77	0.91	1.05
Aerobic decay rate (1/d)	0.085	0.119	0.153	0.17	0.187	0.221	0.255
Anoxic/anaerobic decay rate (1/d)	0.04	0.056	0.072	0.08	0.088	0.104	0.12
K_{I,HNO_2} (mmol/L)	0.0025	0.0035	0.0045	0.005	0.0055	0.0065	0.0075
Maximum specific growth rate (1/d)	0.45	0.63	0.81	0.90	0.99	1.17	1.35

The relative sensitivity is a ratio of the change in model output, such as TAN, to the relative change in model parameter. The analysis could yield a positive or negative result depending on which parameter was being assessed. However, the magnitude of sensitivity, whether positive or negative is the most important aspect. Therefore, the absolute value of each relative sensitivity was calculated. A large number meant that the model was sensitive to a change in that parameter and a small number meant that the model was not sensitive to a change in that parameter. A total of 84 simulations were completed and the most sensitive parameters were determined.

The standard operating condition established in BioWin® was used to compare experimental data obtained from the pilot scale system to modeled results. The kinetic expressions used to define competitive (Equation 4-1), non-competitive (Equation 4-3), uncompetitive (Equation 4-5) and mixed inhibition were included in the growth rate expression for AOB in BioWin®. A user-defined variable was included in the influent, set to an arbitrary unit concentration of 1 mg/L, and treated as the unknown inhibitor. In an attempt to characterize the mechanism of the inhibitor, inhibition constants for the terms, $K_{NH_4^+,I}$, $\hat{\mu}_{AOB,I}$, and $K_{NH_4^+,uncomp.}$ (Equations 4-2, 4-4, and 4-5), were varied until the model TAN removal rates became similar to the results produced by the N removal reactor. Modeled simulations were compared to field results based on similarities in the substrate (TAN) removal rate, $\hat{q}$ (Equation 4-7) (Grady et al., 1999), effluent TAN, and maximum specific growth rate, $\hat{\mu}_{AOB}$.

$$\hat{q} = \frac{\hat{\mu}_{AOB}}{Y_{AOB}} \qquad \text{Equation 4-7}$$

where:

$\hat{q}$ = maximum specific substrate removal rate (mg TAN g VSS COD^{-1} day^{-1})

$\hat{\mu}_{AOB}$ = maximum specific AOB growth rate (day^{-1})

Y_{AOB} = AOB yield (g biomass COD formed per g N oxidized)

4.4 Results and Discussion

4.4.1 Nitrifying activity increased as the fermenter supernatant dilution increased

The results show that fermenter effluent slowed the production of NO_2^- by AOB present in the N removal sludge and, presumably, caused inhibition through some unknown mechanism. Nitrifying activity was negligible when the nitrifying biomass was exposed to concentrated fermenter supernatant and the NGR increased as the fermenter effluent became more dilute (Figure 4-1). A dilution of 1:10 still resulted in a smaller average nitrite generation rate relative to the biomass that did not see any fermenter effluent (measured NGR was 6.18 $\pm$ 1.75 mg NO_2^--N g VSS^{-1} day^{-1}). This result is important because it indicates that an AOB inhibition term is needed to correctly assess nitrification rates in models of the N removal system.

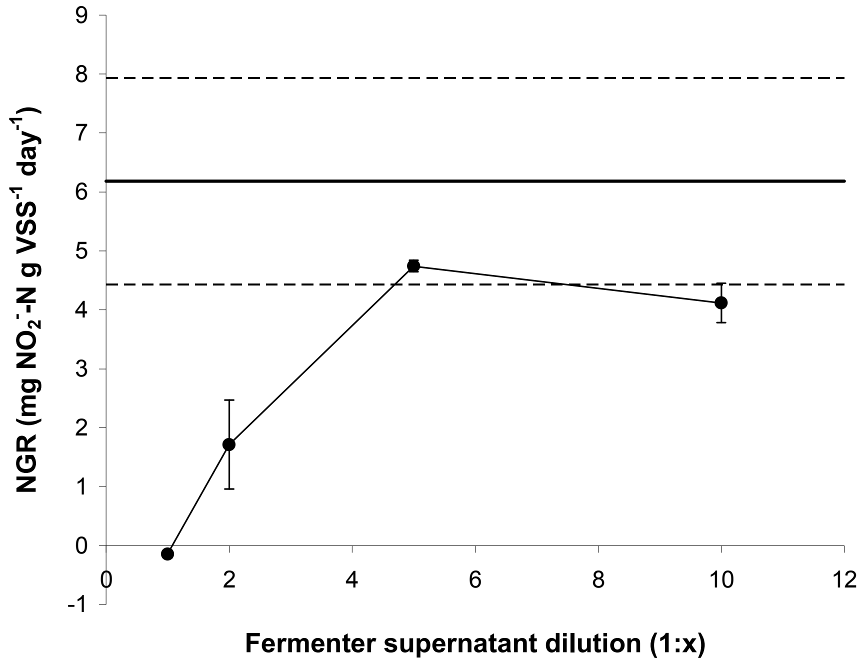

Figure 4-1: NGR versus extent of fermenter dilution (—●—). (A 1:1 dilution value is concentrated fermenter supernatant). The control average NGR with no added fermenter supernatant, (——) is shown with respective standard deviation (– –).

One possible source of nitrification inhibition that could be present in dairy waste is copper sulfate ($CuSO_4$) combined with formaldehyde used in footbaths to prevent hoof disease of the dairy cows. Specifically, the cows at the Virginia Tech dairy walk through a footbath that contains approximately 85 mg/L Cu^{2+} and 7% formaldehyde twice a week. While the specific concentration of Cu^{2+} in the waste itself is unknown, researchers have shown that Cu^{2+} does reduce the growth rate of nitrifiers as well as decreases their biomass concentrations by compromising their membrane integrity (Hu et al., 2004).

4.4.2 BioWin® modeling indicates that nitrifier inhibition occurred, but a definitive model cannot be determined with the current data set.

AOB kinetic and stoichiometric parameters were assessed by considering changes in effluent TAN and NO_2^- (Table 4-3). These results suggest that the AOB parameters to which the model is most sensitive are (in order of decreasing sensitivity): maximum specific growth rate, NH_3 half saturation constant, aerobic decay rate, anoxic/anaerobic decay rate, yield and inhibition constant for nitrous acid. While the actual sensitivities are different for the two base line scenarios (DOs of 0.8 and 2.0 mg/L), the order of decreasing sensitivity is the same. Therefore, the most critical baseline condition, BL_1 was evaluated for the model calibration.

Table 4-3: AOB model sensitivities to varying kinetic and stoichiometric parameters calculated using Equation 4-6.

AOB Maximum Sensitivity	BL_1 (DO = 0.8 mg/L)		BL_2 (DO = 2.0 mg/L)	
Biowin Parameter	TAN	NO_2^-	TAN	NO_2^-
Yield [mg COD / mg N]	0.2	0.1	0.2	0.0
Substrate [NH_4^+] half saturation coefficient. mgN/L	0.9	0.4	0.9	0.3
Aerobic decay rate [1/d]	0.5	0.2	0.6	0.2
Anoxic/Anaerobic decay rate [1/d]	0.2	0.1	0.2	0.1
Nitrous acid inhibition coefficient (KiHNO$_2$ [mmol/L])	0.002	0.001	0.002	0.000
Max specific growth rate [1/d]	23.7	2.2	8.8	0.9

As a result of the sensitivity analysis, the impact of inhibition on the maximum specific growth rate and substrate (TAN) half saturation coefficient estimates for AOB were considered using models of competitive, non-competitive, mixed and uncompetitive inhibition. The patterns of TAN removal for each inhibition mechanism were compared to the actual field results obtained from the average of two cross cycle analyses performed on the pilot plant when the DO was set to 0.8 and 0.9 mg/L (Table 4-4). Specifically, the TAN removal rates of the pilot plant were approximately a third of the observed TAN removal rate determined using the kinetic and stoichiometric BioWin® defaults for AOB. (Table 4-4).

While the modeled TAN removal rates (as determined by linear regression) were similar for each inhibition mechanism tested in BioWin®, the TAN was removed in a non-linear fashion. This was not consistent with the TAN removal observed in the pilot scale study where TAN was removed linearly and suggests that other factors were contributing to the variation between the model and field results. Another factor that is known to impact the kinetics of nitrification is the hydrolysis rate of particulate and high molecular weight soluble organic compounds. Particulate organic nitrogen hydrolysis is linked to this factor and, therefore, can affect the rate of nitrification in a nitrifying bioreactor. Therefore, the default BioWin® hydrolysis rate was adjusted in an attempt to fit the model data to the field results.

Table 4-4: Biowin modeling results of various inhibition mechanisms using the default BioWin® hydrolysis rate.

Data set	TAN removal rate Mg N L^{-1} day^{-1} ± standard deviation (mgN/L)	Correlation coefficient R^2	$\hat{\mu}_{AOB}$ day^{-1}	$K_{NH_4^+}$ mg/L-N
Field data (average of DO levels 0.8 and 0.9 mg/L)	-3.18 ± 0.33	0.9874	N/A[1]	N/A[1]
Not Inhibited (BioWin® defaults used)	-9.74	0.9946	0.9[2]	0.7[2]
Competitive	-3.48	0.9558	0.9[2]	2.7
Non-competitive	-3.37	0.9695	0.525	0.7[2]
Un-competitive	-3.66	0.977	0.4	0.001
Mixed	-3.44	0.9663	0.6	0.93

[1]Not detected
[2]BioWin® default

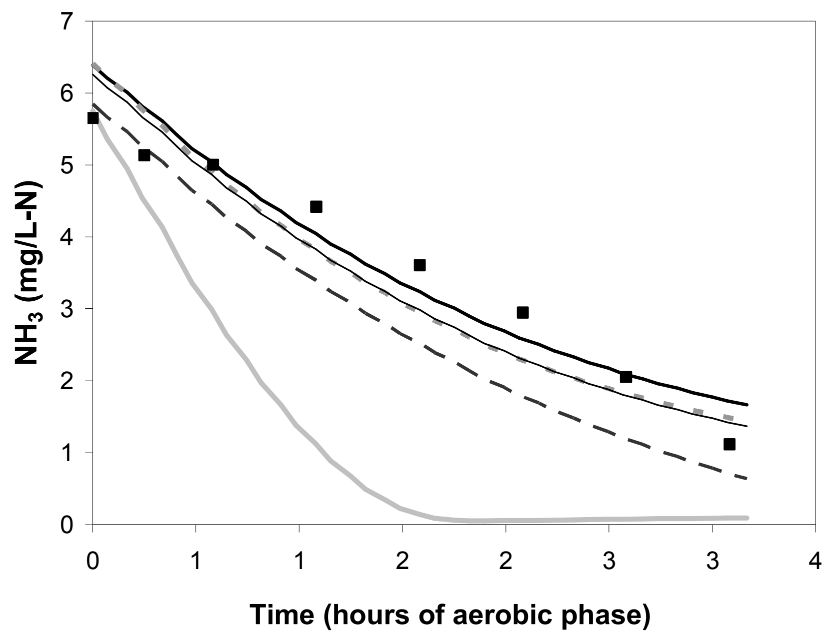

Figure 4-2: Best fit scenarios for inhibition mechanisms of uncompetitive (– – ·), non-competitive (——), competitive (– ·), and mixed (——) were compared to both the field data (■) and the uninhibited model results (——) using the default BioWin® hydrolysis rate.

The hydrolysis rate was reduced by approximately 50% of the default value in BioWin® for each of best fit solutions of each inhibition mechanism. The results show that the reduced hydrolysis rate did predict a more accurate representation of the field data (Figure 4-3, Table 4-5).

Table 4-5: Biowin modeling results of various inhibition mechanisms using a reduced BioWin® hydrolysis rate.

Data set	TAN removal rate mgN/L day^{-1} ± standard deviation (mgN/L)	Correlation coefficient R^2	$\hat{\mu}_{AOB}$ day^{-1}	$K_{NH_4^+}$ mg/L-N
Field data (average of DO levels 0.8 and 0.9 mg/L)	-3.18 ± 0.33	0.9874	N/A[1]	N/A[1]
Not Inhibited (BioWin® defaults used)	-8.24	0.9945	0.9[2]	0.7[2]
Competitive	-3.09	0.9895	0.9[2]	2.7
Non-competitive	-2.91	0.9951	0.525	0.7[2]
Un-competitive	-3.19	0.9976	0.4	0.001
Mixed	-2.98	0.9943	0.6	0.93

[1]Not detected
[2]BioWin® default

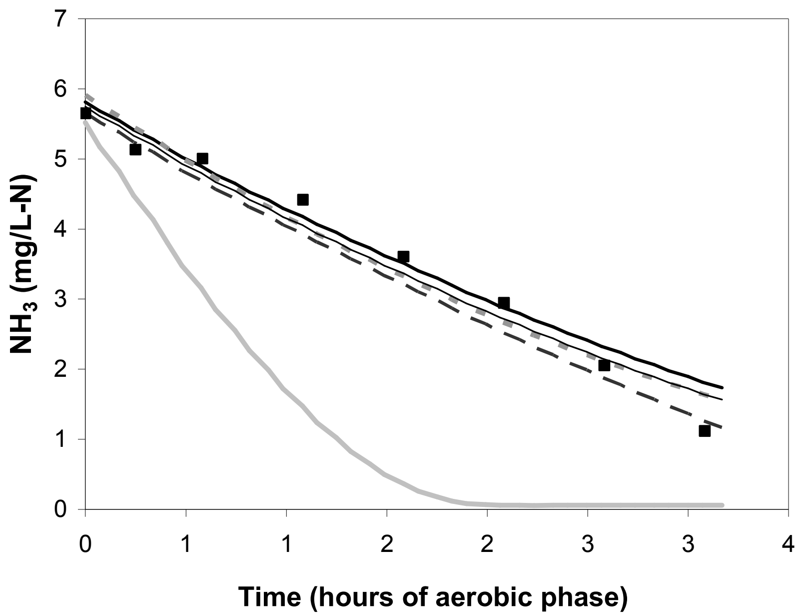

Figure 4-3: Best fit scenarios for inhibition mechanisms of uncompetitive (– – ·), non-competitive (——), competitive (▬ ·), and mixed (——) using a decreased BioWin® hydrolysis rate closely resembled the field data (■) compared to the uninhibited model results (——).

As mentioned previously, Cu^{2+} has been shown to reduce the AOB biomass concentration by compromising the membrane integrity. Reduced biomass concentration also results when the hydrolysis rate is decreased because less TAN is produced by hydrolysis and, therefore, affects AOB growth. It is possible that the changed hydrolysis rate improved the model fit to the data because it served as a surrogate for reflecting the reduced amount AOB biomass, when in fact an inhibitor may have been the cause (as opposed to slowed hydrolylsis). Therefore, while the identity of the inhibitor is still unknown, the concentration of Cu^{2+} is of particular interest and needs to be determined to determine if our theory of copper-induced nitrification inhibition is feasible.

4.5 Conclusion

The results of this study clearly show an increase in nitrifying activity as the fermenter supernatant became more dilute, which confirmed the presence of a nitrification inhibitor in fermented dairy manure. However, the identity of the inhibitor or its exact mechanism is unknown. Our results do show that the inhibitor was biodegradable under aerobic conditions to some extent as witnessed by sustained nitrifying activity in the reactor compared to negligible nitrifying activity when exposed to the concentrated fermenter supernatant in the NGR test.

Competitive, non-competitive, un-competitive and mixed inhibition terms were added to the most sensitive kinetic parameters, maximum specific growth rate, and the substrate half saturation coefficient equations in BioWin® and were used to determine the probable mechanism of the inhibitor. Model results best resembled the field results when the un-competitive inhibition function was used but the fit was not substantially different than the other mechanisms tested. Therefore, further research must be conducted to confirm the mechanism, identify the inhibitor, and define the adjustments that need to be made to existing model parameters. These steps will allow for proper design and operation of N removal systems for AFOs.

4.6 References

Anthonisen, A. C., Loehr, R. C., Prakasam, T. B. S. and Srinath, E. G. (1976). Inhibition of nitrification by ammonia and nitrous acid. *Journal Water Pollution Control Federation*, **48**(5), 835-852.

APHA. (1998). *Standard Methods for the Examination of Water and Wastewater. 21st ed*. American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF).

Beck, J. L., Love, N. G., Gilmore, K. R., Knowlton, K. F. and Ogejo, J. A. (2007). Nitrogen removal from dairy waste using deammonification fuelled by fermented dairy manure. In preparation for submission to *Bioresource Technology*.

Campolongo, F. and Saltelli, A. (1997). Sensitivity analysis of an environmental model: an application of different analysis methods. *Reliability Engineering and System Safety*, **57**(1), 49-69.

Eilersen, A. M., Henze, M. and Kloft, L. (1994). Effect of volatile fatty acids and trimethylamine on nitrification in activated sludge. *Water Research*, **28**(6), 1329-1336.

Grady, L. C., Daigger, G. T. and Lim, H. C. (1999). *Biological Wastewater Treatment*. Marcel Dekker, Inc., New York, NY.

Hao, O. and Chen, J. (1994). Factors Affecting Nitrite Buildup In Submerged Filter System. *Journal Of Environmental Engineering-ASCE* **120**(5), 1298-1307.

Hockenbury, M. and Grady, C. (1977). Inhibition of nitrification - effects of selected organic compounds. *Journal of Water Pollution Control Federation*, **49**, 768-777

Hu, Z., Chandran, K., Grasso, D. and Smets, B. F. (2004). Comparison of nitrification inhibition by metals in batch and continuous flow reactors. *Water Research*, **38**(18), 3949-3959.

Jones, R. M., Bye, C. M. and Dold, P. L. (2005). Nitrification parameter measurement for plant design: experience and experimental issues CD with new methods. *Water Science and Technology*, **52**(10-11), 461-468.

Kelly, R. T., Henriques, I. D. S. and Love, N. G. (2004). Chemical inhibition of nitrification in activated sludge. *Biotechnology and Bioengineering*, **85**(6), 683-694.

Knowlton, K. F., Love, N. G. and Parsons, C. M. (2005). Dietary phosphorus effects on characteristics of mechanically separated dairy manure. *Transactions of the ASAE*, **48**(3), 1253-1258.

Lee, Y.-W., Ong, S.-K. and Sato, C. (1997). Effects of heavy metals on nitrifying bacteria. *Water Science and Technology*, **36**(12), 69-74.

Nowak, O., Svardal, K. and Schweighofer, P. (1995). The dynamic behavior of nitrifying activated sludge systems influenced by inhibiting wastewater compounds. *Water Science and Technology*, **31**(2), 115-124.

Rawn, J. D. (1989). *Biochemistry*. Neil Patterson, Burlington, NC, U.S.A.

Reynolds, T. D. and Richards, P. A. (1996). *Unit Operations and Processes in Environmental Engineering*. *2nd ed*. PWS Publishing, Washington, D.C.

Tchobanoglous, G., Burton, F. L. and Stensel, H. D. (2003). *Wastewater Engineering: Treatment and Reuse*. *4th ed*. Metcalf and Eddy, McGraw-Hill, Boston.

5 ENGINEERING SIGNIFICANCE

The findings from this research are most important in relation to the balancing of nutrients such that they are optimized for crop fertilization but not produced in excess. In addition to TAN, other types of nutrients and organics are present in dairy waste that can all contribute to eutrophication if applied in excess. Most notably, phosphorus (P), is a nutrient that is of interest and is commonly removed in a biological nutrient removal (BNR) system. However, the oxidized products of nitrification, nitrite (NO_2^-) and nitrate (NO_3^-) can impede P removal through competition between the bacteria responsible for P removal (phosphate accumulating organisms, PAOs) and denitrifying heterotrophs for a common substrate, volatile fatty acids (VFAs) (Grady et al., 1999). Although single sludge systems exist that can effectively remove N and P biologically in domestic wastewater treatment systems, these configurations are not practical for application in AFOs. Therefore, N and P removal at an AFO would be most effectively deployed as part of a split treatment system where a portion of the waste flow would remove N and the other would remove P. This would allow flexibility and careful control of the optimization of nutrients for crop fertilization while minimizing excess production. The treated effluents could then be blended creating a final effluent that is lower in both N and P before being land applied. However, the N and P removal systems would be dependent on sufficient bioavailable COD:N and bioavailable COD:P ratios in the waste at the end of anaerobic stabilization (before land application). If a sufficient bioavailable COD:N ratio is found in the waste at the end of anaerobic stabilization, the N removal system studied for this project could be a successful strategy for removing N in the N removal side stream.

The goal of achieving N removal via NO_2^- only was not achieved with this system because competition between ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB) ceased after all TAN was oxidized. This allowed for residual DO to be available to NOB for NO_2^- oxidation. However, the results from the cross cycle analyses suggest that cycled aeration in a series of aerobic phases may be a successful strategy for N removal. There was a period of time during each cross cycle where the $NO_2^-:NO_3^-$

ratio was significantly high and ranged from 3.0 to 6.9. On average, the maximum ratio occurred after 1.5 aerobic hours. Therefore, a successful strategy would be to limit the time of aeration to 1.5 hours where any NO_2^- and/or NO_3^- produced in the aerobic zone could be denitrified in a subsequent anoxic zone. This process could then be repeated until all inorganic N was removed. This would provide the benefits of removing N via the NO_2^- pathway.

Furthermore, it would limit the duration of the aerobic phase to the minimum required for nitrification. The COD removed in the aerobic phase is undesirable because it creates a costly aeration demand for a process that could be accomplished through anaerobic stabilization. However, the findings from this research suggested that some COD had to be oxidized during the aerobic zone to support heterotrophic denitrification through a process known as simultaneous nitrification-dentrification (SND).

A reasonable N balance of measured N species, and estimates of biomass growth suggested that simultaneous nitrification-denitrification was occurring in the N removal reactor and was most apparent at DO concentrations between 0.8 and 1.3 mg/L. This phenomenon is important because it reduced the concentrations of NO_2^- and NO_3^- at the end of the aerobic zone, thus reducing the duration of the anoxic phase required for denitrification. Therefore, the total volume of the N removal system could be decreased.

The mechanism of SND is dependent on the concentration of electron donor present in the waste which was found to be sufficient for this project. The SCOD concentrations produced by the fermenter were consumed well before they could be used in the anoxic phase for denitrification. However, complete denitrification was still observed in all cross cycles tested. This suggests that slowly biodegradable COD in the waste itself was used as the electron donor. Therefore the addition of an external electron donor would not be required by an AFO for denitrification and would translate to a cost savings compared to conventional BNR systems.

The minimum DO required for nitrification was determined during this study, thereby generating an economic benefit. Using the configurations tested for this project, the minimum DO required for biological TAN oxidation was found to be 0.8 mg/L. However, keeping the DO at this exact concentration in a full scale system is a difficult task and would most likely be kept in a range of values that are above 0.8 mg/L. Even so, the system would require a precise monitoring and aeration strategy to minimize energy costs. DO control could be accomplished with DO probes that control variable speed blowers such that the aeration decreases but is not completely eliminated when DO levels rise above a user defined set-point.

Finally, the success of the N removal system is dependent on accurate characterization of the waste before the reactors are designed and constructed. For example, periodic measurements of organic N showed that approximately 35% of the TKN was organic N but was not accounted for in this research. High SRT values typically associated with anaerobic stabilization can cause the release of TAN through ammonification of organic N and cell lysis that needs to be accounted for in nutrient balance calculations (Grady et al., 1999; MWPS, 1993). Furthermore, the solids concentration, waste dilution requirements, and organics concentration need to be assessed before the design of an N removal system is completed. In particular, a nitrification inhibitor was found to exist in dairy waste that must be accounted for in the design of a full scale N removal system. Typical kinetic values for AOB were found to be inaccurate when modeling this system. Therefore, experiments must be conducted to adequately identify and characterize the inhibitor to ensure the accuracy of the system design. The presence of an inhibitor will most likely require higher SRT values compared to conventional BNR systems which translates to larger reactor basins. Nevertheless, the system used for this research achieved 100% TAN removal for the majority of the project and could be implemented to remove excess N for an AFO.

5.1 References

Grady, L. C., Daigger, G. T. and Lim, H. C. (1999). *Biological Wastewater Treatment*. Marcel Dekker, Inc., New York, NY.

MWPS. (1993). *Livestock waste facilities handbook. 3rd ed*. MidWest Plan Service, Iowa State University, Ames, Iowa.

APPENDIX A: TAN removal data

A.1 BIOWIN MODELING AND DESIGN OF PILOT SCALE NITROGEN REMOVAL SYSTEM

Table A-1: Components of BioWin® model.

Component description	BioWin® item	Comments
Fermenter effluent	COD influent	
Inhibitor influent	Variable stream input	Flow = 0.36 L/day, operated on same frequency as the fermenter effluent. Unknown inhibitor was UD1 = 10,000 mg/L such that the final concentration in the system influent after mixing was 1 mg/L.
N removal reactor	Variable volume bioreactor	Operated as a sequencing batch reactor to mimic the actual operation of the pilot scale system
System effluent	COD effluent	

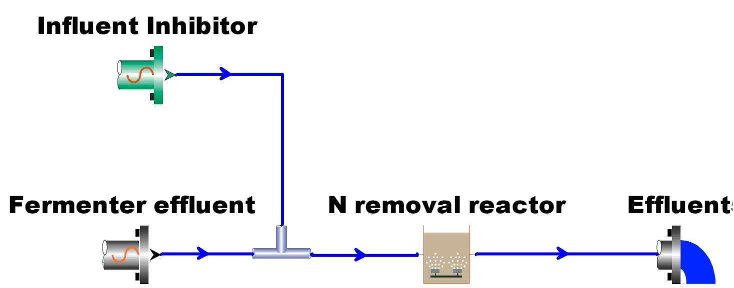

Figure A-1 BioWin® modeling configuration with influent inhibitor option. Inhibitor concentration was set to 0 mg/L for initial system design.

Table A-2 Influent concentrations for BioWin® simulations to model the pilot scale N removal system.

Influent measurements and parameters	Value	Unit	Comments
Flow	2.5	L/min	Flow for 2 min every 8 hours
Total COD	9728	mg COD/L	field data
Total Kjeldahl Nitrogen	501	mg N/L	field data
Total P	225	mg P/L	EBPR field data
Nitrate N	0	mg N/L	field data
pH	7.3		field data
Alkalinity ($CaCO_3$ equivalent)	300	mg $CaCO_3$/L	pH switches turned off, so this value is insignificant
Calcium	80	mg/L	BioWin default
Magnesium	15	mg/L	BioWin default
Dissolved oxygen	0	mg O_2/L	field data
Effluent filtered COD	551	mg COD/L	field data (1.5 μm filter)
Influent filtered COD	2540	mg COD/L	field data (1.5 μm filter)
Influent acetate	969	mg COD/L	filed data
Influent TAN	125	mg N/L	field data
Influent ortho-phosphate	100	mg P/L	EBPR field data
Influent VSS	13770	mg/L	field data
Influent TSS	17000	mg/L	field data

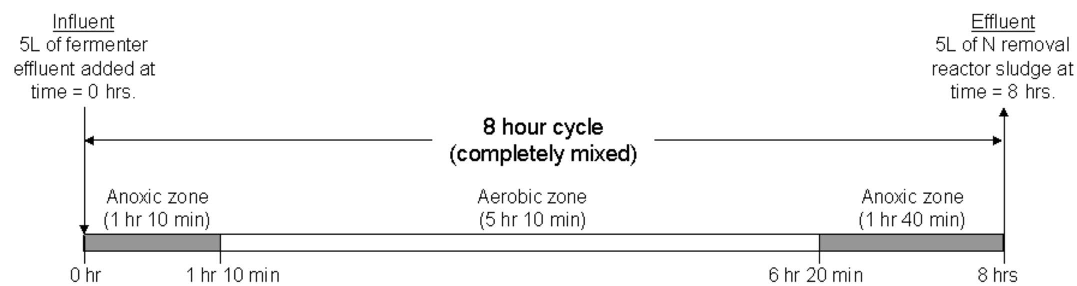

Figure A-2 Cross cycle profile and aeration times for pilot scale reactor and BioWin® simulations.

Table A-3 COD influent fractions and ratios that characterize system feed.

Influent fraction	Value	Unit
Particulate substrate COD:VSS ratio	0.5200	
Particulate inert COD:VSS ratio	0.5200	
Fbs - Readily biodegradable (including Acetate)	0.1027	g COD/g of total COD
Fac - Acetate	0.9695	g COD/g of readily biodegradable COD
Fxsp - Non-colloidal slowly biodegradable	0.7500	g COD/g of slowly degradable COD
Fus - Unbiodegradable soluble	0.0565	g COD/g of total COD
Fup - Unbiodegradable particulate	0.4600	g COD/g of total COD
Fna - Ammonia	0.2495	g NH_3-N/g TKN
Fnox - Particulate organic nitrogen	0.5000	g N/g Organic N
Fnus - Soluble unbiodegradable TKN	0.0200	g N/g TKN
FupN - N:COD ratio for unbiodegradable part. COD	0.0350	g N/g COD
Fpo_4 - Phosphate	0.4444	g PO_4-P/g TP
FupP - P:COD ratio for influent unbiodegradable part. COD	0.0110	g P/g COD
FZbh - Non-poly-P heterotrophs	0.0001	g COD/g of total COD
FZbm - Anoxic methanol utilizers	0.0001	g COD/g of total COD
FZaob - Ammonia oxidizers	0.0001	g COD/g of total COD
FZnob - Nitrite oxidizers	0.0001	g COD/g of total COD
FZamob - Anaerobic ammonia oxidizersz	0.0001	g COD/g of total COD
FZbp - PAOs	0.0001	g COD/g of total COD
FZbpa - Propionic acetogens	0.0001	g COD/g of total COD
FZbam - Acetoclastic methanogens	0.0001	g COD/g of total COD
FZbhm - H_2-utilizing methanogens	0.0001	g COD/g of total COD

With an SRT of 6 days, Biowin® model predictions yielded a wide range of percent aeration values to achieve minimum total effluent N while maintaining a low SRT (Figure A-3). Therefore, an initial SRT of 6 days and percent aeration of 35% were selected. However, the reactor yielded poor performance at these values for days 0-98.

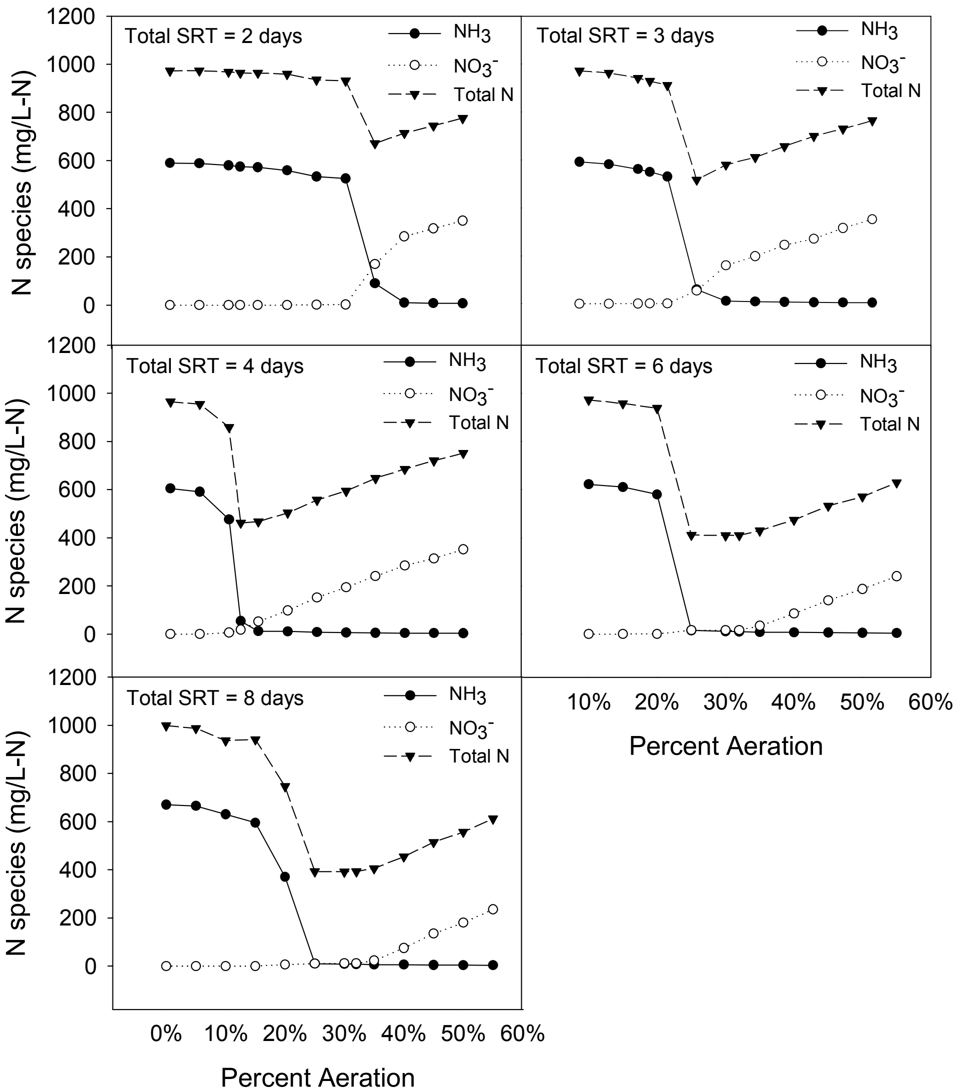

Figure A-3 Model predicted N-species outputs at varying percent aeration for each specified total SRT (2-8 days). A total SRT of 6 days was initially chosen (above).

A.2 INDIVIDUAL SYSTEM FEED CHARACTERISTICS AS REPORTED IN TABLE 3-3

On average, a new bucket of thawed waste contained 15 L of concentrated feed and the system used 5 L of concentrated feed per day. Therefore, a new bucket was used every three days. New batches of manure were collected and processed through the solids-separator on 12/01/07, 2/2/07, 4/8/07, 7/7/07, and 7/28/07 (Days of operation: 93, 156, 221, 311, and 332).

Table A-4: System feed TAN concentrations.

Date	Day	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Average (mg/L-N)	Maximum - Average (mg/L-N)
12/22/2006	114	121.7	128.8	125.3	3.6
1/16/2007	139	149.3	152.8	151.1	1.7
1/22/2007	145	109.6	129.6	119.6	10.0
2/5/2007	159	199.8	212.0	205.9	6.1
2/12/2007	166	147.7	161.0	154.3	6.7
2/19/2007	173	98.6	105.8	102.2	3.6
3/12/2007	194	154.4	157.6	156.0	1.6
3/19/2007	201	72.6	86.5	79.6	6.9
4/4/2007	217	139.6	142.6	141.1	1.5
4/9/2007	222	83.1	112.3	97.7	14.6
4/24/2007	237	216.2	235.3	225.7	9.6
5/14/2007	257	157.5	167.3	162.4	4.9
5/21/2007	264	131.2	134.7	132.9	1.8
5/29/2007	272	182.6	188.1	185.4	2.7
6/6/2007	280	86.0	89.8	87.9	1.9
6/12/2007	286	112.4	156.0	134.2	21.8
6/23/2007	297	209.1	245.4	227.2	18.2
7/6/2007	310	121.0	131.1	126.1	5.1
8/28/2007	363	223.0	223.1	223.1	0.1
	Average:			149.3	
	Standard deviation:			46.1	

Table A-5: Feed soluble COD (SCOD) concentrations.

Date	Day	Rep 1 SCOD (mg/L)	Rep 2 SCOD (mg/L)	Average (mg/L)	Maximum - Average (mg/L)
4/24/2007	237	3395	3395	3395	0
5/14/2007	257	3301	3321	3311	10
5/21/2007	264	4401	4614	4507	106
5/29/2007	272	3630	3688	3659	29
6/6/2007	280	3782	3803	3793	10
7/6/2007	310	3595	3515	3555	40
7/24/2007	328	4289	N/A	4289	0
	Average:			3787	
	Standard deviation:			451	

Table A-6: System feed total suspended solids (TSS) concentrations.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)
9/26/2006	27	6500	7100	8600	7400	1082
10/3/2006	34	9100	8100	9500	8900	721
10/10/2006	41	10900	12000	12000	11633	635
10/17/2006	48	9700	9200	9000	9300	361
10/24/2006	55	9600	9500	9700	9600	100
11/7/2006	69	6900	8000	7900	7600	608
11/14/2006	76	8700	8100	8800	8533	379
11/28/2006	90	9000	7700	8300	8333	651
12/5/2006	97	9500	9500	10600	9867	635
1/2/2007	125	13600	13300	12900	13267	351
1/16/2007	139	11500	11600	11200	11433	208
1/22/2007	145	10500	11600	10700	10933	586
2/5/2007	159	10000	10200	10800	10333	416
2/12/2007	166	14900	15700	15900	15500	529
2/19/2007	173	12000	11500	12500	12000	500
3/12/2007	194	13100	11500	12500	12367	808
3/19/2007	201	12400	13800	8200	11467	2914
3/26/2007	208	13200	12300	13300	12933	551
4/9/2007	222	13500	10500	10700	11567	1677
4/24/2007	237	8500	7800	8400	8233	379
5/14/2007	257	10200	10200	N/A	10200	0
5/21/2007	264	11800	12000	12400	12067	306
5/29/2007	272	10700	16700	16300	14567	3355
6/6/2007	280	8500	9000	9400	8967	451
6/11/2007	285	12900	12900	12500	12767	231
6/23/2007	297	11700	11300	12000	11667	351
7/6/2007	310	9700	10600	10200	10167	451
7/24/2007	328	7900	N/A	N/A	7900	N/A
8/28/2007	363	18600	16600	18200	17800	1058
		Average			10941	
		Standard deviation			2450	

Table A-7: System feed volatile suspended solids (VSS) concentrations.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)
9/26/2006	27	4300	5400	6500	5400	1100
10/3/2006	34	7500	6900	7800	7400	458
10/10/2006	41	10100	11500	11200	10933	737
10/17/2006	48	8400	7400	7100	7633	681
10/24/2006	55	8600	8900	8400	8633	252
11/7/2006	69	6900	7100	6800	6933	153
11/14/2006	76	8700	8000	8300	8333	351
11/28/2006	90	9300	7600	8200	8367	862
12/5/2006	97	9300	9800	11100	10067	929
1/2/2007	125	12300	11800	11400	11833	451
1/16/2007	139	9900	9600	9900	9800	173
1/22/2007	145	8700	9300	8500	8833	416
2/5/2007	159	8700	8500	9100	8767	306
2/12/2007	166	14300	14700	14800	14600	265
2/19/2007	173	9900	9200	10100	9733	473
3/12/2007	194	11100	10300	10100	10500	529
3/19/2007	201	9300	11300	5800	8800	2784
3/26/2007	208	9100	8500	10100	9233	808
4/9/2007	222	11900	9200	9400	10167	1504
4/24/2007	237	7400	6800	7200	7133	306
5/14/2007	257	9100	8800	N/A	8950	212
5/21/2007	264	9500	10100	10500	10033	503
5/29/2007	272	8800	14100	14100	12333	3060
6/6/2007	280	7400	7000	7900	7433	451
6/11/2007	285	11600	11600	10800	11333	462
6/23/2007	297	10100	9900	10100	10033	115
7/6/2007	310	8600	9300	9100	9000	361
7/24/2007	328	7000	N/A	N/A	7000	N/A
		Average			9360	
		Standard deviation			2370	

A.3 N REMOVAL SYSTEM PERFORMANCE DATA FOR FIGURE 3-2

Table A-8: Fermenter effluent TAN concentrations.

Date	Day	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Average (mg/L-N)	Maximum - Average (mg/L-N)
8/30/06	0	633.7	637.7	635.7	2.0
9/5/06	6	573.9	632.6	603.3	29.4
9/7/06	8	508.8	520.8	514.8	6.0
9/10/06	11	427.9	437.8	432.8	5.0
9/13/06	14	623.8	625.7	624.8	1.0
9/15/06	16	663.7	668.7	666.2	2.5

Date	Day	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Average (mg/L-N)	Maximum - Average (mg/L-N)
9/18/06	19	647.8	682.7	665.2	17.4
9/21/06	22	657.7	648.7	653.2	4.5
9/24/06	25	699.7	704.7	702.2	2.5
9/26/06	27	599.8	592.8	596.3	3.5
9/28/06	29	458.8	457.8	458.3	0.5
9/30/06	31	500.8	499.8	500.3	0.5
10/3/06	34	304.9	294.9	299.9	5.0
11/3/06	65	168.3	164.3	166.3	2.0
11/7/06	69	585.7	602.3	594.0	8.3
11/10/06	72	355.5	357.5	356.5	1.0
11/13/06	75	257.8	255.2	256.5	1.3
11/28/06	90	132.7	124.0	128.4	4.3
12/5/06	97	123.4	124.1	123.8	0.4
12/9/06	101	248.1	269.6	258.9	10.7
12/16/06	108	270.3	340.0	305.2	34.8
12/19/06	111	366.2	340.3	353.3	12.9
12/22/06	114	238.6	232.9	235.8	2.9
1/2/07	125	253.0	198.4	225.7	27.3
1/8/07	131	261.7	202.2	231.9	29.7
1/10/07	133	159.0	212.7	185.9	26.9
1/12/07	135	408.4	204.1	306.3	102.2
1/16/07	139	309.6	207.0	258.3	51.3
1/22/07	145	129.5	122.8	126.1	3.3
2/2/07	156	265.8	241.7	253.8	12.0
2/5/07	159	246.7	243.7	245.2	1.5
2/19/07	173	232.0	194.6	213.3	18.7
2/23/07	177	188.9	236.5	212.7	23.8
3/1/07	183	255.8	262.6	259.2	3.4
3/2/07	184	294.4	224.1	259.2	35.2
3/7/07	189	208.2	165.1	186.6	21.5
3/9/07	191	246.7	192.3	219.5	27.2
3/12/07	194	211.6	211.6	211.6	0.0
3/16/07	198	341.2	160.7	251.0	90.2
3/19/07	201	160.7	126.4	143.6	17.1
3/23/07	205	166.8	212.1	189.5	22.7
3/26/07	208	205.1	128.5	166.8	38.3
3/30/07	212	173.8	225.2	199.5	25.7
4/4/07	217	126.4	220.2	173.3	46.9
4/9/07	222	240.4	150.6	195.5	44.9
4/24/07	237	105.4	74.4	89.9	15.5
4/27/07	240	144.0	251.4	197.7	53.7
5/3/07	246	295.8	270.7	283.3	12.6
5/14/07	257	376.1	364.5	370.3	5.8
5/21/07	264	169.2	208.8	189.0	19.8
5/29/07	272	233.9	257.6	245.8	11.9
6/6/07	280	211.7	210.2	210.9	0.7
6/12/07	286	170.9	205.0	188.0	17.0
6/23/07	297	241.3	221.3	231.3	10.0

Date	Day	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Average (mg/L-N)	Maximum - Average (mg/L-N)
7/6/07	310	254.7	236.1	245.4	9.3
7/24/07	328	97.1	107.2	102.2	5.1
8/28/07	363	283.3	285.1	284.2	0.9
Day 0-363		Average		305.3	
		Standard deviation		166.2	
Day 98-363		Average		225.9	
		Standard deviation		60.0	

Table A-9: N removal reactor effluent TAN concentration. Zero concentration indicates not detected.

Date	Day	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Average (mg/L-N)	Maximum - Average (mg/L-N)
9/5/06	6	362.9	366.9	364.9	2.0
9/7/06	8	422.8	419.8	421.3	1.5
9/10/06	11	394.8	393.8	394.3	0.5
9/13/06	14	450.8	460.8	455.8	5.0
9/15/06	16	499.8	503.8	501.8	2.0
9/18/06	19	530.8	520.8	525.8	5.0
9/21/06	22	592.8	589.8	591.3	1.5
9/24/06	25	603.8	N/A	603.8	0.0
9/26/06	27	604.8	603.8	604.3	0.5
9/28/06	29	573.8	578.8	576.3	2.5
9/30/06	31	469.8	470.8	470.3	0.5
10/3/06	34	438.8	437.8	438.3	0.5
11/7/06	69	130.3	134.2	132.2	2.0
11/10/06	72	193.9	181.2	187.6	6.4
11/13/06	75	140.2	140.2	140.2	0.0
11/28/06	90	46.1	40.7	43.4	2.7
12/5/06	97	68.3	84.3	76.3	8.0
12/9/06	101	10.9	7.8	9.3	1.5
12/16/06	108	3.8	5.8	4.8	1.0
12/19/06	111	0.0	0.0	0.0	0.0
12/22/06	114	0.0	0.0	0.0	0.0
1/2/07	125	7.7	7.7	7.7	0.0
1/8/07	131	23.0	25.9	24.5	1.4
1/10/07	133	20.0	36.3	28.1	8.2
1/12/07	135	23.0	21.1	22.1	1.0
1/16/07	139	36.5	31.7	34.1	2.4
1/19/07	142	35.0	35.0	35.0	0.0
1/22/07	145	26.9	26.9	26.9	0.0
1/29/07	152	60.4	51.8	56.1	4.3
2/2/07	156	6.8	6.2	6.5	0.3
2/5/07	159	1.8	2.2	2.0	0.2
2/7/07	161	0.0	0.0	0.0	0.0
2/9/07	163	1.3	0.7	1.0	0.3
2/12/07	166	0.9	0.7	0.8	0.1
2/19/07	173	4.6	5.8	5.2	0.6
2/23/07	177	2.4	2.3	2.4	0.1
3/1/07	183	0.0	0.0	0.0	0.0
3/2/07	184	2.7	2.6	2.6	0.0
3/7/07	189	0.7	0.5	0.6	0.1
3/9/07	191	3.3	1.9	2.6	0.7
3/13/07	195	0.0	0.0	0.0	0.0
3/13/07	195	0.0	0.0	0.0	0.0
3/16/07	198	0.0	0.0	0.0	0.0
3/19/07	201	1.4	2.7	2.0	0.7
3/20/07	202	1.4	1.9	1.7	0.3
3/21/07	203	0.7	1.1	0.9	0.2

Date	Day	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Average (mg/L-N)	Maximum - Average (mg/L-N)
3/22/07	204	2.0	1.4	1.7	0.3
3/23/07	205	5.4	5.4	5.4	0.0
3/26/07	208	9.8	9.8	9.8	0.0
3/28/07	210	9.8	9.8	9.8	0.0
3/30/07	212	27.2	26.2	26.7	0.5
4/4/07	217	31.6	32.7	32.1	0.5
4/9/07	222	3.3	4.4	3.8	0.5
4/10/07	223	1.1	1.1	1.1	0.0
4/13/07	226	0.0	0.0	0.0	0.0
4/19/07	232	0.0	0.0	0.0	0.0
4/20/07	233	0.0	0.0	0.0	0.0
4/20/07	234	0.0	0.0	0.0	0.0
4/23/07	236	0.0	0.0	0.0	0.0
4/24/07	237	0.7	0.8	0.7	0.0
4/26/07	239	0.0	0.0	0.0	0.0
4/27/07	240	0.0	0.0	0.0	0.0
4/30/07	243	0.0	0.0	0.0	0.0
5/3/07	247	0.0	0.0	0.0	0.0
5/6/07	250	0.0	0.0	0.0	0.0
5/8/07	252	0.0	0.0	0.0	0.0
5/12/07	255	0.0	0.0	0.0	0.0
5/14/07	257	1.3	2.0	1.6	0.4
5/16/07	259	0.0	0.0	0.0	0.0
5/21/07	264	1.3	1.3	1.3	0.0
5/22/07	265	0.0	0.0	0.0	0.0
5/23/07	266	0.0	0.0	0.0	0.0
5/29/07	272	0.0	0.0	0.0	0.0
5/31/07	274	0.0	0.0	0.0	0.0
6/3/07	277	0.0	0.0	0.0	0.0
6/6/07	280	0.0	0.0	0.0	0.0
6/11/07	285	0.0	0.0	0.0	0.0
6/20/07	294	0.0	0.0	0.0	0.0
7/9/07	313	0.0	0.0	0.0	0.0
7/18/07	322	0.0	0.0	0.0	0.0
7/28/07	332	0.0	0.0	0.0	0.0
8/7/07	342	0.0	0.0	0.0	0.0
8/14/07	349	10.0	14.0	12.0	2.0
8/16/07	351	13.1	16.2	14.7	1.6
8/27/07	363	21.3	22.7	22.0	0.7

A.4 CROSS CYCLE GRAPHS

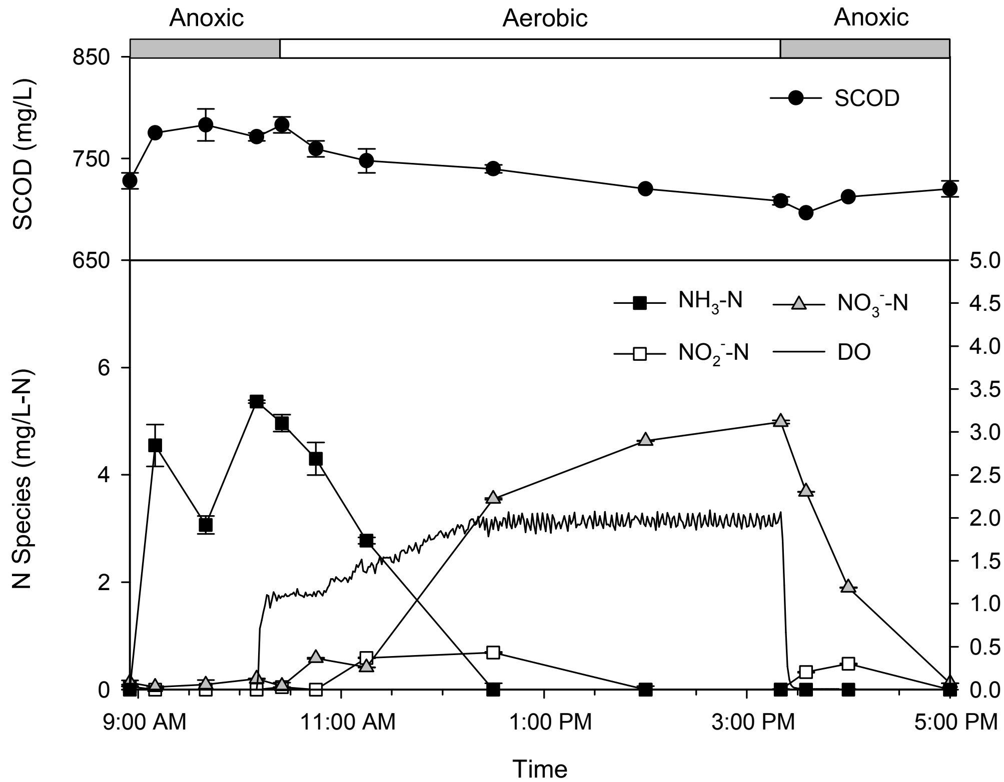

Figure A-4 Cross cycle performed on day 233 at DO = 2.0 mg/L.

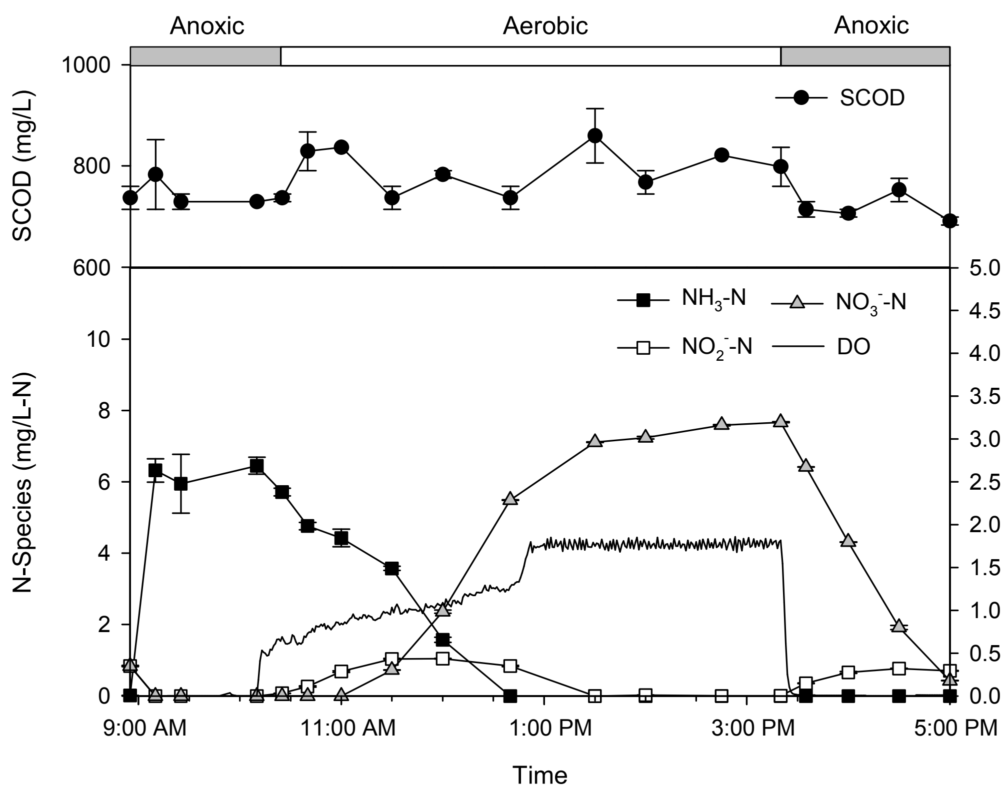

Figure A-5: Cross cycle performed on day 243 at DO = 1.8 mg/L.

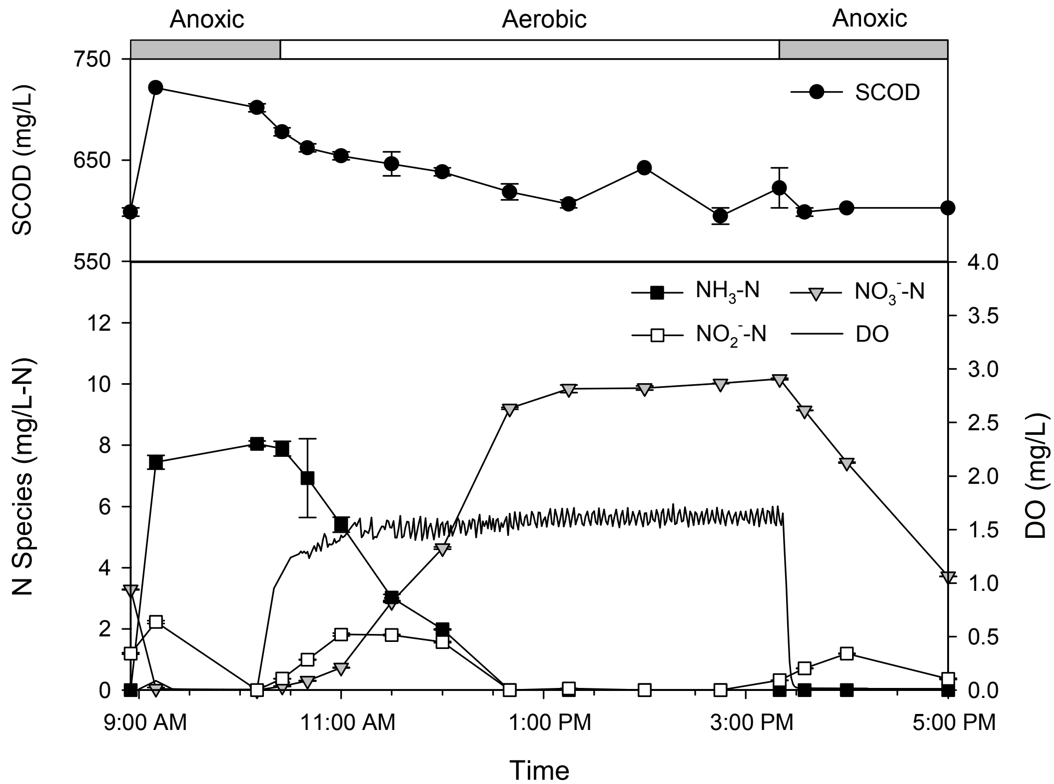

Figure A-6: Cross cycle performed on day 251 at DO = 1.6 mg/L.

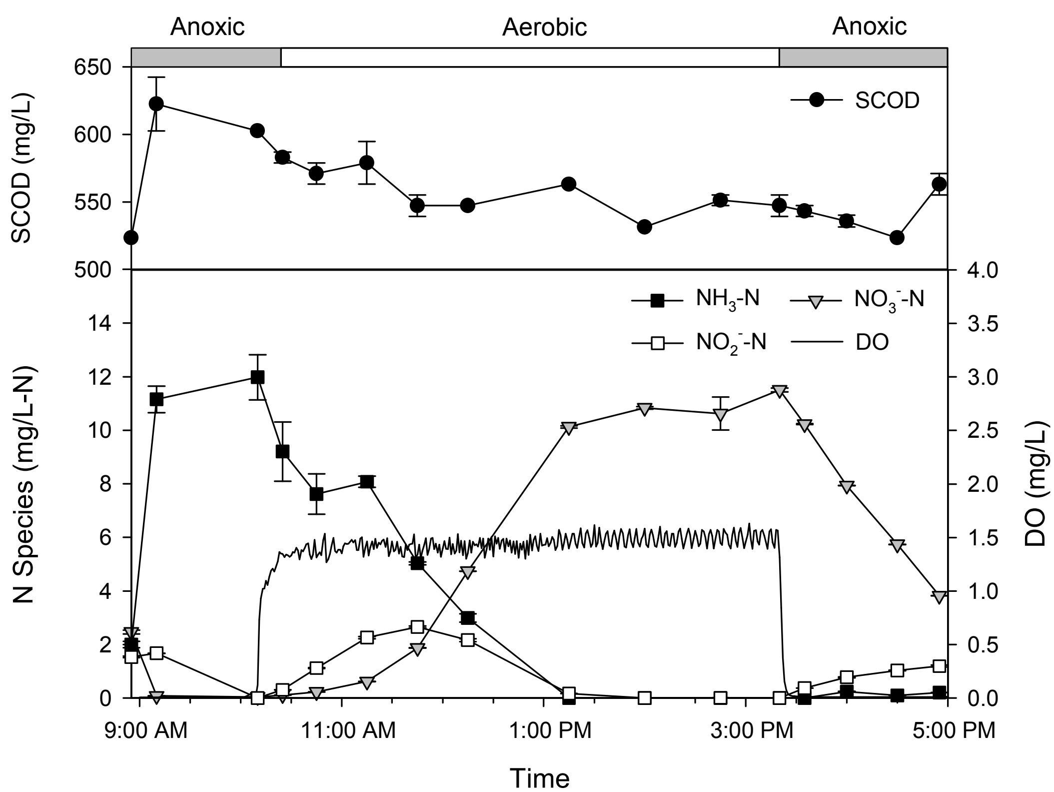

Figure A-7: Cross cycle performed on day 259 at DO = 1.5 mg/L.

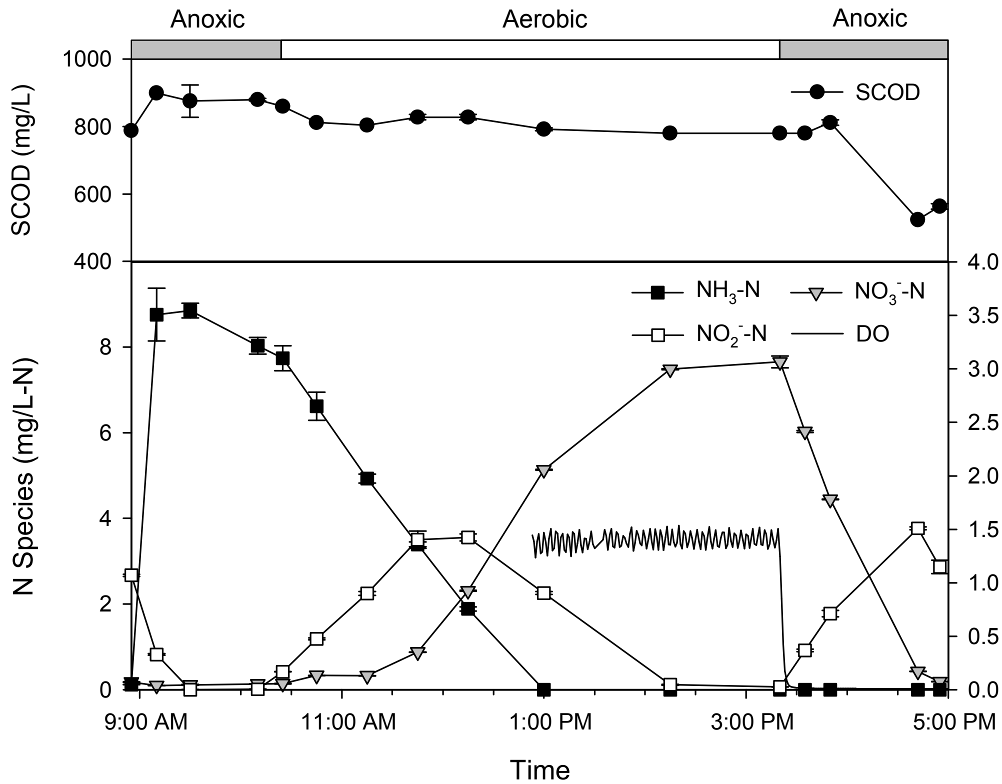

Figure A-8: Cross cycle performed on day 266 at DO = 1.4 mg/L.

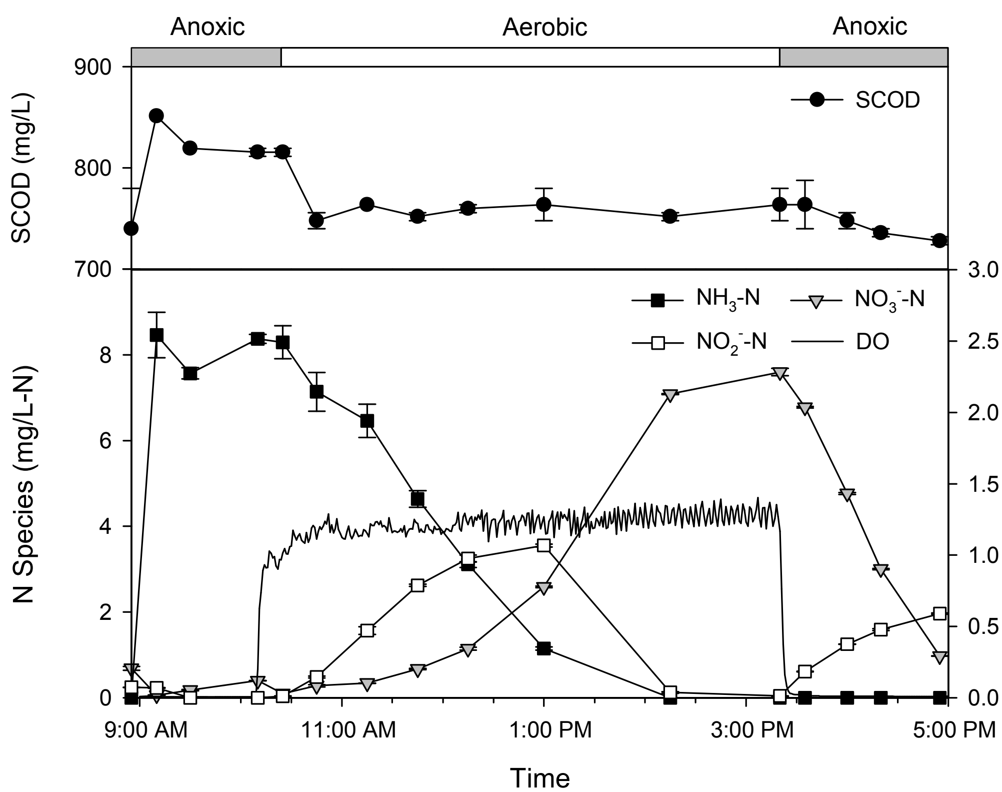

Figure A-9: Cross cycle performed on day 274 at DO = 1.3 mg/L.

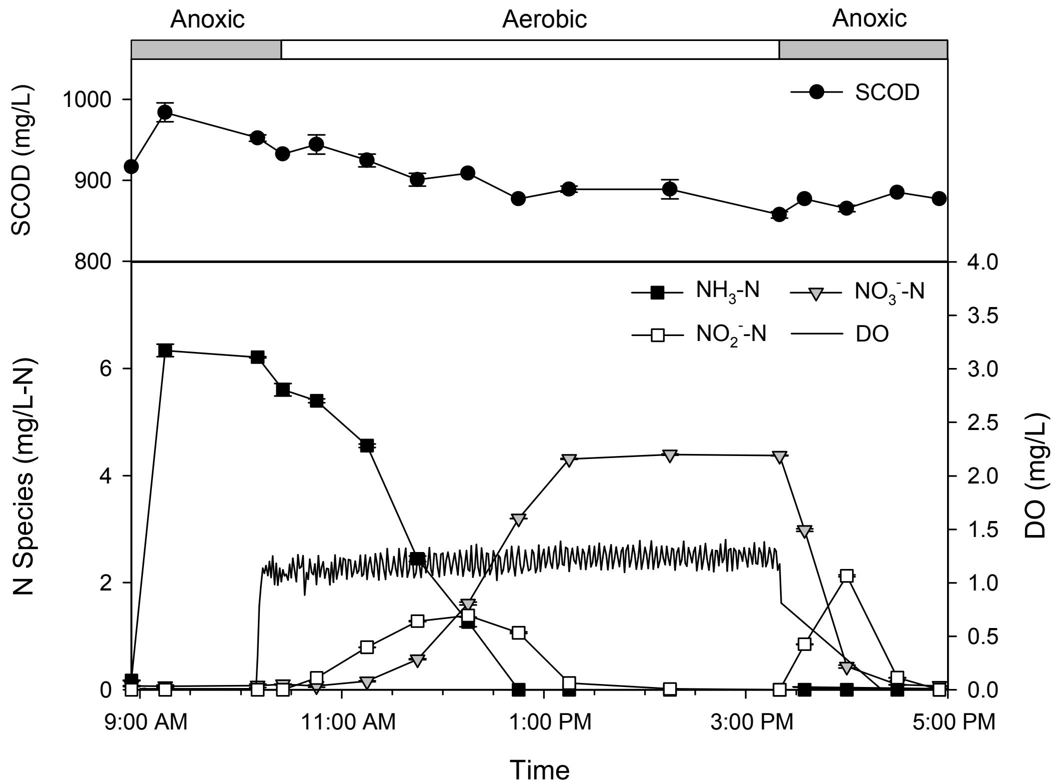

Figure A-10: Cross cycle performed on day 294 at DO = 1.2 mg/L.

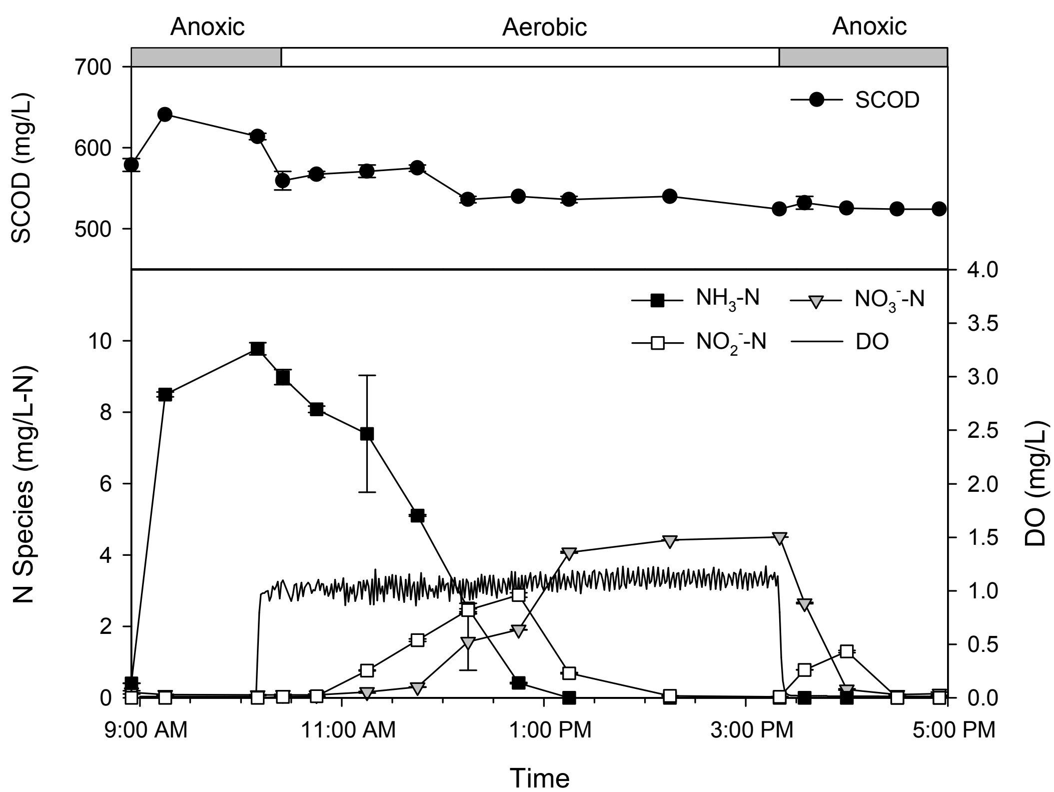

Figure A-11: Cross cycle performed on day 313 at DO = 1.1 mg/L.

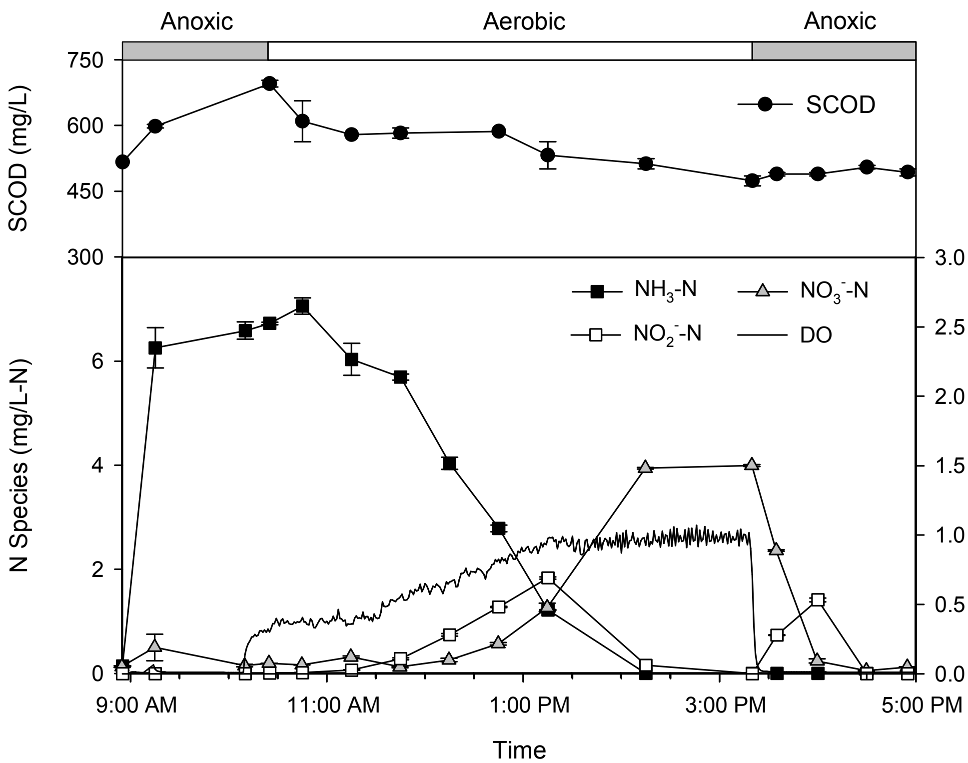

Figure A-12: Cross cycle performed on day 322 at DO = 1.0 mg/L.

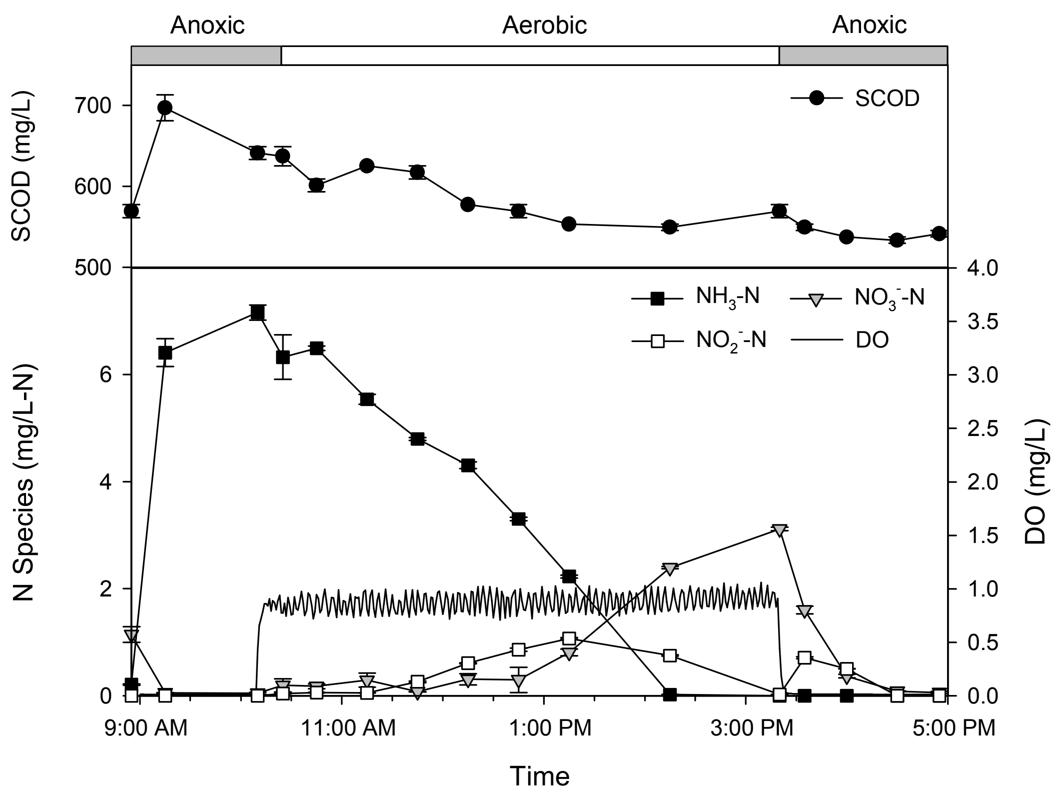

Figure A-13: Cross cycle performed on day 332 at DO = 0.9 mg/L.

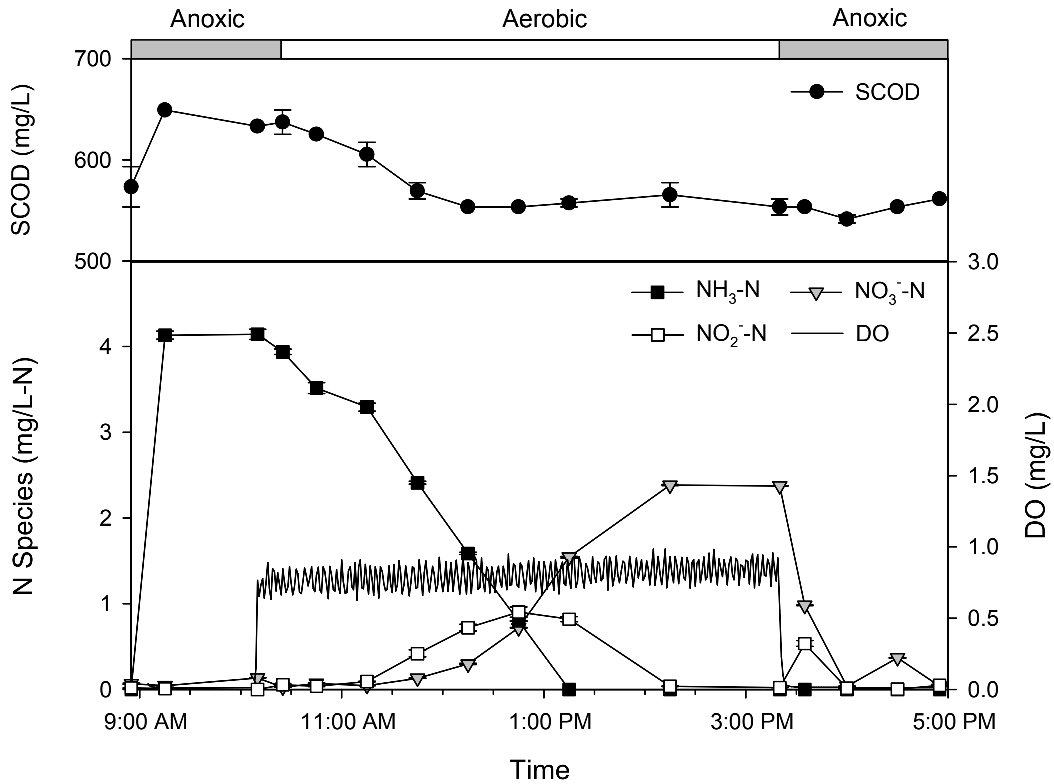

Figure A-14: Cross cycle performed on day 342 at DO = 0.8 mg/L.

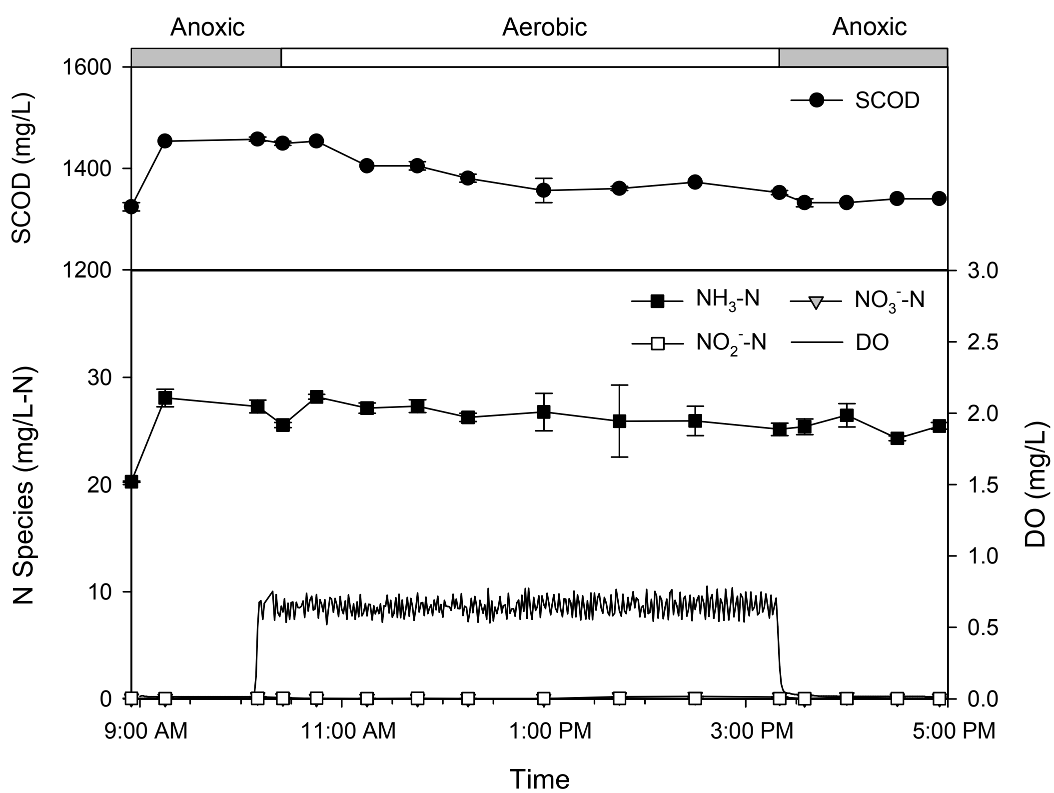

Figure A-15: Cross cycle performed on day 362 at DO = 0.7 mg/L.

Table A-10: Cross cycle dates and day of operation.

Date of cross cycle	Day of operation	Date of Manure collection
4/20/2007	233	4/8/2007
4/30/2007	243	4/8/2007
5/8/2007	251	4/8/2007
5/16/2007	259	4/8/2007
5/23/2007	266	4/8/2007
5/31/2007	274	4/8/2007
6/14/2007	288	4/8/2007
6/20/2007	294	4/8/2007
7/9/2007	313	7/7/2007
7/18/2007	322	7/7/2007
7/28/2007	332	7/7/2007
8/7/2007	342	7/28/2007
8/27/2007	362	7/28/2007

Table A-11: Cross cycle TAN concentration data. Zero concentration indicates not detected.

Date	Time	DO (mg/L)	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Rep 3 TAN (mg/L-N)	Rep 4 TAN (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
3/20/2007	8:55 AM	1.7	1.90	0.86	1.38	3.99	2.03	1.37
3/20/2007	9:10 AM	1.7			6.08	8.42	7.25	1.66
3/20/2007	9:34 AM	1.7	4.51	4.77	5.56	5.82	5.16	0.62
3/20/2007	10:07 AM	1.7	6.08	6.34	4.77	5.82	5.75	0.69
3/20/2007	10:27 AM	1.7	5.56	6.34	6.34	6.60	6.21	0.45
3/20/2007	12:35 PM	1.7	1.94	1.94	3.24	4.10	2.80	1.06
3/20/2007	2:00 PM	1.7	1.51	3.45	2.16	2.16	2.32	0.81
3/20/2007	3:21 PM	1.7	1.94	2.16	1.08	0.86	1.51	0.64
3/20/2007	3:35 PM	1.7	1.94	1.73	2.16	2.16	2.00	0.21
3/20/2007	5:00 PM	1.7	1.29	1.51	1.94	1.94	1.67	0.32
3/22/2007	8:55 AM	1.7	0.34	1.12	1.12	1.12	0.93	0.39
3/22/2007	9:10 AM	1.7	4.25	5.03	8.69	8.42	6.60	2.28
3/22/2007	9:35 AM	1.7	5.82	4.77	6.60	6.34	5.88	0.81
3/22/2007	10:07 AM	1.7	4.25	5.29	6.60	6.34	5.62	1.07
3/22/2007	10:25 AM	1.7	5.03	5.56	8.16	6.60	6.34	1.38
3/22/2007	1:50 PM	1.7	1.94	1.51	1.94	1.94	1.83	0.22
3/22/2007	2:45 PM	1.7	2.16	2.37	2.37	2.37	2.32	0.11
3/22/2007	3:21 PM	1.7	1.51	1.51	1.29	1.29	1.40	0.12
3/22/2007	3:35 PM	1.7	1.94	1.73	1.51	1.51	1.67	0.21
3/22/2007	4:50 PM	1.7	1.94	2.16	1.73	1.08	1.73	0.47
4/20/2007	8:55 AM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	9:10 AM	2.0	4.19	4.16	4.80	5.04	4.55	0.44
4/20/2007	9:40 AM	2.0	5.71	5.42	5.18	5.15	5.37	0.26
4/20/2007	10:10 AM	2.0	2.58	2.58	3.49	3.60	3.06	0.56
4/20/2007	10:25 AM	2.0	4.59	4.51	5.37	5.39	4.96	0.48
4/20/2007	10:45 AM	2.0	4.35	4.27	4.27	4.32	4.30	0.04
4/20/2007	11:15 AM	2.0	2.53	2.58	3.01	2.98	2.78	0.26
4/20/2007	12:30 PM	2.0	0.00	0.00	0.00	0.00	0.00	0.00

Date	Time	DO (mg/L)	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Rep 3 TAN (mg/L-N)	Rep 4 TAN (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
4/20/2007	2:00 PM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	3:20 PM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	3:35 PM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	4:00 PM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	5:00 PM	2.0	0.04	0.07	0.00	0.00	0.03	0.03
4/30/2007	8:55 AM	1.8	0.07	0.01	0.00	0.00	0.02	0.03
4/30/2007	9:10 AM	1.8	5.89	5.93	6.75	6.69	6.32	0.47
4/30/2007	9:25 AM	1.8	6.98	6.98	4.90	4.92	5.95	1.19
4/30/2007	10:10 AM	1.8	6.73	6.73	6.10	6.24	6.45	0.33
4/30/2007	10:25 AM	1.8	5.53	5.65	5.78	5.89	5.71	0.16
4/30/2007	10:40 AM	1.8	4.60	4.66	4.88	4.90	4.76	0.16
4/30/2007	11:00 AM	1.8	4.79	4.75	4.08	4.08	4.43	0.40
4/30/2007	11:30 AM	1.8	3.63	3.68	3.47	3.51	3.57	0.10
4/30/2007	12:00 PM	1.8	1.42	1.48	1.57	1.84	1.58	0.19
4/30/2007	12:40 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	1:30 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	2:00 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	2:45 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	3:20 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	3:35 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	4:00 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	4:30 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	5:00 PM	1.8	0.13	0.13	0.13	0.13	0.13	0.00
5/8/2007	8:55 AM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	9:10 AM	1.6	7.11	7.28	7.59	7.80	7.44	0.31
5/8/2007	10:10 AM	1.6	8.06	8.20	7.89	8.03	8.04	0.13
5/8/2007	10:25 AM	1.6	8.12	8.20	7.59	7.64	7.89	0.32
5/8/2007	10:40 AM	1.6	8.79	8.12	5.32	5.49	6.93	1.78
5/8/2007	11:00 AM	1.6	5.84	5.59	5.11	5.09	5.41	0.37
5/8/2007	11:30 AM	1.6	2.81	2.92	3.17	3.21	3.03	0.19
5/8/2007	12:00 PM	1.6	1.99	2.03	1.95	1.97	1.98	0.03
5/8/2007	12:40 PM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	1:15 PM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	2:00 PM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	2:45 PM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	3:20 PM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	3:35 PM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	4:00 PM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	5:00 PM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/16/2007	8:55 AM	1.5	2.22	2.17	1.76	1.81	1.99	0.24
5/16/2007	9:10 AM	1.5	10.58	10.72	11.67	11.65	11.15	0.59
5/16/2007	10:10 AM	1.5	11.16	11.11	12.69	12.96	11.98	0.98
5/16/2007	10:25 AM	1.5	8.00	8.08	10.36	10.38	9.21	1.35
5/16/2007	10:45 AM	1.5	8.42	8.46	6.74	6.84	7.61	0.95
5/16/2007	11:15 AM	1.5	8.46	7.95	7.95	7.93	8.08	0.26
5/16/2007	11:45 AM	1.5	4.92	5.04	5.04	5.11	5.03	0.08
5/16/2007	12:15 PM	1.5	2.64	2.95	3.17	3.19	2.99	0.26
5/16/2007	1:15 PM	1.5	0.04	0.04	0.00	0.00	0.02	0.02

Date	Time	DO (mg/L)	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Rep 3 TAN (mg/L-N)	Rep 4 TAN (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
5/16/2007	2:00 PM	1.5	0.00	0.00	0.00	0.00	0.00	0.00
5/16/2007	2:45 PM	1.5	0.00	0.00	0.00	0.00	0.00	0.00
5/16/2007	3:20 PM	1.5	0.00	0.00	0.00	0.00	0.00	0.00
5/16/2007	3:35 PM	1.5	0.00	0.00	0.00	0.00	0.00	0.00
5/16/2007	4:00 PM	1.5	0.16	0.16	0.30	0.33	0.24	0.09
5/16/2007	4:30 PM	1.5	0.11	0.13	0.09	0.06	0.10	0.03
5/16/2007	5:00 PM	1.5	0.23	0.18	0.18	0.21	0.20	0.02
5/23/2007	8:55 AM	1.4	0.15	0.11	0.11	0.11	0.12	0.02
5/23/2007	9:10 AM	1.4	9.38	9.59	7.97	8.09	8.76	0.85
5/23/2007	9:30 AM	1.4	9.05	9.05	8.59	8.72	8.85	0.23
5/23/2007	10:10 AM	1.4	8.22	8.30	7.72	7.89	8.03	0.27
5/23/2007	10:25 AM	1.4	7.39	7.39	8.01	8.18	7.74	0.41
5/23/2007	10:45 AM	1.4	6.31	6.10	7.05	7.01	6.62	0.49
5/23/2007	11:15 AM	1.4	5.02	5.14	4.81	4.77	4.93	0.18
5/23/2007	11:45 AM	1.4	3.31	3.35	3.35	3.56	3.39	0.11
5/23/2007	12:15 PM	1.4	2.02	1.98	1.77	1.77	1.89	0.13
5/23/2007	1:00 PM	1.4	0.00	0.00	0.00	0.00	0.00	0.00
5/23/2007	2:15 PM	1.4	0.00	0.00	0.00	0.00	0.00	0.00
5/23/2007	3:20 PM	1.4	0.00	0.00	0.00	0.00	0.00	0.00
5/23/2007	3:35 PM	1.4	0.00	0.00	0.00	0.00	0.00	0.00
5/23/2007	3:50 PM	1.4	0.00	0.00	0.00	0.00	0.00	0.00
5/23/2007	4:42 PM	1.4	0.00	0.00	0.36	0.00	0.09	0.18
5/23/2007	4:55 PM	1.4	0.00	0.00	0.00	0.00	0.00	0.00
5/31/2007	8:55 AM	1.3	0.00	0.00	0.00	0.00	0.00	0.00
5/31/2007	9:10 AM	1.3	7.72	7.95	9.18	9.03	8.47	0.74
5/31/2007	9:30 AM	1.3	7.79	7.68	7.42	7.41	7.57	0.19
5/31/2007	10:10 AM	1.3	8.35	8.19	8.54	8.43	8.38	0.15
5/31/2007	10:25 AM	1.3	8.73	8.80	7.72	7.95	8.30	0.55
5/31/2007	10:45 AM	1.3	6.55	6.59	7.74	7.69	7.14	0.66
5/31/2007	11:15 AM	1.3	6.94	7.02	5.92	5.97	6.46	0.60
5/31/2007	11:45 AM	1.3	4.34	4.37	4.83	5.02	4.64	0.34
5/31/2007	12:15 PM	1.3	3.30	3.08	3.09	2.97	3.11	0.14
5/31/2007	1:00 PM	1.3	1.04	1.37	1.07	1.10	1.15	0.15
5/31/2007	2:15 PM	1.3	0.00	0.00	0.00	0.13	0.03	0.07
5/31/2007	3:20 PM	1.3	0.00	0.00	0.00	0.00	0.00	0.00
5/31/2007	3:35 PM	1.3	0.00	0.00	0.00	0.00	0.00	0.00
5/31/2007	4:00 PM	1.3	0.00	0.00	0.00	0.00	0.00	0.00
5/31/2007	4:20 PM	1.3	0.25	0.08	0.00	0.00	0.08	0.12
5/31/2007	4:55 PM	1.3	0.00	0.00	0.00	0.01	0.00	0.00
6/20/2007	8:55 AM	1.2	0.08	0.06	0.27	0.27	0.17	0.12
6/20/2007	9:15 AM	1.2	6.23	6.18	6.44	6.51	6.34	0.16
6/20/2007	10:10 AM	1.2	6.19	6.23	6.21	6.21	6.21	0.02
6/20/2007	10:25 AM	1.2	5.45	5.47	5.74	5.76	5.60	0.17
6/20/2007	10:45 AM	1.2	5.41	5.32	5.42	5.44	5.40	0.05
6/20/2007	11:15 AM	1.2	4.52	4.51	4.60	4.61	4.56	0.05
6/20/2007	11:45 AM	1.2	2.54	2.53	2.35	2.37	2.45	0.10
6/20/2007	12:15 PM	1.2	0.97	1.12	1.53	1.44	1.27	0.26
6/20/2007	12:45 PM	1.2	0.00	0.00	0.00	0.00	0.00	0.00

Date	Time	DO (mg/L)	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Rep 3 TAN (mg/L-N)	Rep 4 TAN (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
6/20/2007	1:15 PM	1.2	0.00	0.00	0.00	0.00	0.00	0.00
6/20/2007	2:15 PM	1.2	0.00	0.00	0.00	0.00	0.00	0.00
6/20/2007	3:20 PM	1.2	0.00	0.00	0.00	0.00	0.00	0.00
6/20/2007	3:35 PM	1.2	0.00	0.00	0.00	0.00	0.00	0.00
6/20/2007	4:00 PM	1.2	0.00	0.00	0.00	0.00	0.00	0.00
6/20/2007	4:30 PM	1.2	0.00	0.00	0.00	0.00	0.00	0.00
6/20/2007	4:55 PM	1.2	0.00	0.00	0.08	0.09	0.04	0.05
7/9/2007	8:55 AM	1.1	0.40	0.37	0.40	0.47	0.41	0.04
7/9/2007	9:15 AM	1.1	8.42	8.42	8.57	8.57	8.50	0.08
7/9/2007	10:10 AM	1.1	9.60	9.60	9.93	9.98	9.78	0.21
7/9/2007	10:25 AM	1.1	9.24	9.17	8.73	8.78	8.98	0.26
7/9/2007	10:45 AM	1.1	8.18	8.16	8.02	7.97	8.08	0.11
7/9/2007	11:15 AM	1.1	5.62	5.60	9.17	9.19	7.39	2.06
7/9/2007	11:45 AM	1.1	5.09	5.14	5.12	5.07	5.10	0.03
7/9/2007	12:15 PM	1.1	2.26	2.29	2.70	2.74	2.50	0.26
7/9/2007	12:45 PM	1.1	0.32	0.35	0.49	0.49	0.41	0.09
7/9/2007	1:15 PM	1.1	0.00	0.00	0.00	0.00	0.00	0.00
7/9/2007	2:15 PM	1.1	0.06	0.04	0.00	0.08	0.04	0.04
7/9/2007	3:20 PM	1.1	0.00	0.00	0.00	0.00	0.00	0.00
7/9/2007	3:35 PM	1.1	0.00	0.00	0.00	0.00	0.00	0.00
7/9/2007	4:00 PM	1.1	0.00	0.00	0.00	0.00	0.00	0.00
7/9/2007	4:30 PM	1.1	0.01	0.01	0.04	0.06	0.03	0.02
7/9/2007	4:55 PM	1.1	0.18	0.11	0.18	0.20	0.17	0.04
7/18/2007	8:55 AM	1.0	0.12	0.12	0.14	0.18	0.14	0.03
7/18/2007	9:15 AM	1.0	5.86	5.82	6.75	6.59	6.25	0.48
7/18/2007	10:10 AM	1.0	6.43	6.39	6.71	6.81	6.58	0.20
7/18/2007	10:25 AM	1.0	6.69	6.75	6.71	6.75	6.72	0.03
7/18/2007	10:45 AM	1.0	7.14	7.28	6.85	6.96	7.06	0.19
7/18/2007	11:15 AM	1.0	5.68	5.72	6.35	6.37	6.03	0.38
7/18/2007	11:45 AM	1.0	5.62	5.66	5.80	5.68	5.69	0.08
7/18/2007	12:15 PM	1.0	4.16	4.18	3.91	3.89	4.04	0.16
7/18/2007	12:45 PM	1.0	2.71	2.69	2.86	2.88	2.78	0.10
7/18/2007	1:15 PM	1.0	1.19	1.23	1.21	1.25	1.22	0.03
7/18/2007	2:15 PM	1.0	0.00	0.00	0.00	0.00	0.00	0.00
7/18/2007	3:20 PM	1.0	0.00	0.00	0.00	0.00	0.00	0.00
7/18/2007	3:35 PM	1.0	0.00	0.00	0.00	0.00	0.00	0.00
7/18/2007	4:00 PM	1.0	0.00	0.00	0.02	0.00	0.01	0.01
7/18/2007	4:30 PM	1.0	0.00	0.00	0.00	0.00	0.00	0.00
7/18/2007	4:55 PM	1.0	0.06	0.00	0.00	0.00	0.02	0.03
7/28/2007	8:55 AM	0.9	0.33	0.26	0.09	0.15	0.21	0.11
7/28/2007	9:15 AM	0.9	6.66	6.73	6.11	6.13	6.41	0.33
7/28/2007	10:10 AM	0.9	7.34	7.27	7.01	7.01	7.16	0.17
7/28/2007	10:25 AM	0.9	6.79	6.77	5.83	5.91	6.33	0.53
7/28/2007	10:45 AM	0.9	6.51	6.53	6.42	6.51	6.49	0.05
7/28/2007	11:15 AM	0.9	5.43	5.45	5.56	5.70	5.54	0.12
7/28/2007	11:45 AM	0.9	4.80	4.84	4.80	4.75	4.80	0.04
7/28/2007	12:15 PM	0.9	4.23	4.23	4.38	4.38	4.30	0.09
7/28/2007	12:45 PM	0.9	3.29	3.24	3.33	3.35	3.30	0.05

Date	Time	DO (mg/L)	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Rep 3 TAN (mg/L-N)	Rep 4 TAN (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
7/28/2007	1:15 PM	0.9	2.17	2.21	2.26	2.28	2.23	0.05
7/28/2007	2:15 PM	0.9	0.00	0.02	0.00	0.06	0.02	0.03
7/28/2007	3:20 PM	0.9	0.00	0.00	0.00	0.00	0.00	0.00
7/28/2007	3:35 PM	0.9	0.02	0.00	0.11	0.06	0.05	0.05
7/28/2007	4:30 PM	0.9	0.00	0.13	0.06	0.09	0.07	0.05
7/28/2007	4:55 PM	0.9	0.15	0.13	0.09	0.04	0.10	0.05
8/7/2007	8:55 AM	0.8	0.00	0.00	0.00	0.00	0.00	0.00
8/7/2007	9:15 AM	0.8	4.20	4.17	4.05	4.11	4.13	0.06
8/7/2007	10:10 AM	0.8	4.24	4.15	4.04	4.15	4.14	0.08
8/7/2007	10:25 AM	0.8	3.89	4.00	3.93	3.94	3.94	0.05
8/7/2007	10:45 AM	0.8	3.39	3.50	3.56	3.61	3.52	0.09
8/7/2007	11:15 AM	0.8	3.24	3.24	3.39	3.30	3.29	0.07
8/7/2007	11:45 AM	0.8	2.39	2.39	2.45	2.41	2.41	0.03
8/7/2007	12:15 PM	0.8	1.56	1.56	1.62	1.60	1.59	0.03
8/7/2007	12:45 PM	0.8	0.81	0.81	0.79	0.79	0.80	0.01
8/7/2007	1:15 PM	0.8	0.00	0.00	0.09	0.00	0.02	0.04
8/7/2007	2:15 PM	0.8	0.00	0.00	0.00	0.00	0.00	0.00
8/7/2007	3:20 PM	0.8	0.00	0.00	0.00	0.00	0.00	0.00
8/7/2007	3:35 PM	0.8	0.00	0.00	0.00	0.00	0.00	0.00
8/7/2007	4:00 PM	0.8	0.00	0.00	0.00	0.00	0.00	0.00
8/7/2007	4:30 PM	0.8	0.00	0.00	0.05	0.00	0.01	0.03
8/7/2007	4:55 PM	0.8	0.00	0.00	0.00	0.00	0.00	0.00
8/27/2007	8:55 AM	0.7	20.32	20.24	20.17	20.32	20.26	0.07
8/27/2007	9:15 AM	0.7	29.05	28.74	27.27	27.27	28.08	0.94
8/27/2007	10:10 AM	0.7	27.43	28.12	26.50	27.04	27.27	0.68
8/27/2007	10:25 AM	0.7	25.42	25.26	25.65	25.88	25.55	0.27
8/27/2007	10:45 AM	0.7	28.58	28.20	27.97	28.04	28.20	0.27
8/27/2007	11:15 AM	0.7	26.65	26.73	27.81	27.35	27.14	0.55
8/27/2007	11:45 AM	0.7	27.73	28.04	26.88	26.58	27.31	0.69
8/27/2007	12:15 PM	0.7	26.65	26.65	25.80	25.96	26.27	0.45
8/27/2007	1:00 PM	0.7	28.58	28.43	24.80	25.26	26.77	2.02
8/27/2007	1:45 PM	0.7	22.48	22.64	29.12	29.43	25.92	3.88
8/27/2007	2:30 PM	0.7	24.57	24.57	27.19	27.43	25.94	1.59
8/27/2007	3:20 PM	0.7	24.49	24.64	25.73	25.73	25.15	0.67
8/27/2007	3:35 PM	0.7	26.19	26.03	24.95	24.41	25.40	0.86
8/27/2007	4:00 PM	0.7	25.34	25.42	27.58	27.50	26.46	1.25
8/27/2007	4:30 PM	0.7	24.41	24.57	24.34	23.95	24.32	0.26
8/27/2007	4:55 PM	0.7	25.26	25.11	25.65	25.88	25.47	0.35

Table A-12: Cross cycle NO_2^- concentration data. Zero concentration indicates not detected.

Date	Time	DO mg/L	Rep 1 NO_2^- (mg/L-N)	Rep 2 NO_2^- (mg/L-N)	Rep 3 NO_2^- (mg/L-N)	Rep 4 NO_2^- (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
3/20/2007	8:55 AM	1.7	1.90	0.86	1.38	3.99	2.03	1.37
3/20/2007	9:10 AM	1.7	N/A	N/A	6.08	8.42	7.25	1.66

Date	Time	DO mg/L	Rep 1 NO_2^- (mg/L-N)	Rep 2 NO_2^- (mg/L-N)	Rep 3 NO_2^- (mg/L-N)	Rep 4 NO_2^- (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
3/20/2007	9:34 AM	1.7	4.51	4.77	5.56	5.82	5.16	0.62
3/20/2007	10:07 AM	1.7	6.08	6.34	4.77	5.82	5.75	0.69
3/20/2007	10:27 AM	1.7	5.56	6.34	6.34	6.60	6.21	0.45
3/20/2007	12:35 PM	1.7	1.94	1.94	3.24	4.10	2.80	1.06
3/20/2007	2:00 PM	1.7	1.51	3.45	2.16	2.16	2.32	0.81
3/20/2007	3:21 PM	1.7	1.94	2.16	1.08	0.86	1.51	0.64
3/20/2007	3:35 PM	1.7	1.94	1.73	2.16	2.16	2.00	0.21
3/20/2007	5:00 PM	1.7	1.29	1.51	1.94	1.94	1.67	0.32
3/22/2007	8:55 AM	1.7	0.34	1.12	1.12	1.12	0.93	0.39
3/22/2007	9:10 AM	1.7	4.25	5.03	8.69	8.42	6.60	2.28
3/22/2007	9:35 AM	1.7	5.82	4.77	6.60	6.34	5.88	0.81
3/22/2007	10:07 AM	1.7	4.25	5.29	6.60	6.34	5.62	1.07
3/22/2007	10:25 AM	1.7	5.03	5.56	8.16	6.60	6.34	1.38
3/22/2007	1:50 PM	1.7	1.94	1.51	1.94	1.94	1.83	0.22
3/22/2007	2:45 PM	1.7	2.16	2.37	2.37	2.37	2.32	0.11
3/22/2007	3:21 PM	1.7	1.51	1.51	1.29	1.29	1.40	0.12
3/22/2007	3:35 PM	1.7	1.94	1.73	1.51	1.51	1.67	0.21
3/22/2007	4:50 PM	1.7	1.94	2.16	1.73	1.08	1.73	0.47
4/20/2007	8:55 AM	2.0	0.07	0.07	0.07	0.03	0.06	0.02
4/20/2007	9:10 AM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	9:40 AM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	10:10 AM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	10:25 AM	2.0	0.04	0.04	0.04	0.05	0.04	0.00
4/20/2007	10:45 AM	2.0	0.00	0.00	0.01	0.00	0.00	0.01
4/20/2007	11:15 AM	2.0	0.57	0.60	0.60	0.60	0.59	0.01
4/20/2007	12:30 PM	2.0	0.67	0.69	0.69	0.72	0.69	0.02
4/20/2007	2:00 PM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	3:20 PM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/20/2007	3:35 PM	2.0	0.31	0.30	0.34	0.34	0.32	0.02
4/20/2007	4:00 PM	2.0	0.48	0.46	0.48	0.50	0.48	0.02
4/20/2007	5:00 PM	2.0	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	8:55 AM	1.8	0.83	0.82	0.83	0.88	0.84	0.03
4/30/2007	9:10 AM	1.8	0.00	0.00	0.01	0.00	0.00	0.01
4/30/2007	9:25 AM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	10:10 AM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	10:25 AM	1.8	0.08	0.07	0.06	0.08	0.07	0.01
4/30/2007	10:40 AM	1.8	0.25	0.24	0.25	0.32	0.27	0.04
4/30/2007	11:00 AM	1.8	0.71	0.67	0.72	0.65	0.69	0.03
4/30/2007	11:30 AM	1.8	1.02	1.03	1.04	1.06	1.04	0.02
4/30/2007	12:00 PM	1.8	1.06	1.04	1.04	1.04	1.04	0.01
4/30/2007	12:40 PM	1.8	0.82	0.81	0.83	0.88	0.84	0.03
4/30/2007	1:30 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	2:00 PM	1.8	0.01	0.04	0.01	0.04	0.03	0.02
4/30/2007	2:45 PM	1.8	0.00	0.00	0.00	0.00	0.00	0.00
4/30/2007	3:20 PM	1.8	0.00	0.00	0.05	0.00	0.01	0.03
4/30/2007	3:35 PM	1.8	0.38	0.35	0.35	0.35	0.36	0.01
4/30/2007	4:00 PM	1.8	0.64	0.73	0.63	0.64	0.66	0.05

Date	Time	DO mg/L	Rep 1 NO_2^- (mg/L-N)	Rep 2 NO_2^- (mg/L-N)	Rep 3 NO_2^- (mg/L-N)	Rep 4 NO_2^- (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
4/30/2007	4:30 PM	1.8	0.78	0.77	0.77	0.75	0.77	0.01
4/30/2007	5:00 PM	1.8	0.71	0.70	0.71	0.70	0.71	0.01
5/8/2007	8:55 AM	1.6	1.17	1.16	1.24	1.21	1.20	0.04
5/8/2007	9:10 AM	1.6	2.21	2.16	2.29	2.23	2.22	0.06
5/8/2007	10:10 AM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	10:25 AM	1.6	0.36	0.36	0.38	0.38	0.37	0.01
5/8/2007	10:40 AM	1.6	0.98	0.98	1.01	1.00	0.99	0.02
5/8/2007	11:00 AM	1.6	1.74	1.82	1.88	1.82	1.81	0.06
5/8/2007	11:30 AM	1.6	1.78	1.78	1.82	1.80	1.80	0.02
5/8/2007	12:00 PM	1.6	1.56	1.53	1.59	1.58	1.57	0.03
5/8/2007	12:40 PM	1.6	0.01	0.00	0.00	0.00	0.00	0.00
5/8/2007	1:15 PM	1.6	0.03	0.04	0.05	0.05	0.04	0.01
5/8/2007	2:00 PM	1.6	0.00	0.00	0.01	0.00	0.00	0.00
5/8/2007	2:45 PM	1.6	0.00	0.00	0.00	0.00	0.00	0.00
5/8/2007	3:20 PM	1.6	0.31	0.31	0.33	0.32	0.32	0.01
5/8/2007	3:35 PM	1.6	0.70	0.69	0.73	0.71	0.71	0.02
5/8/2007	4:00 PM	1.6	1.20	1.20	1.20	1.17	1.19	0.01
5/8/2007	5:00 PM	1.6	0.34	0.34	0.42	0.36	0.36	0.04
5/16/2007	8:55 AM	1.5	1.47	1.54	1.57	1.54	1.53	0.04
5/16/2007	9:10 AM	1.5	1.68	1.67	1.66	1.68	1.67	0.01
5/16/2007	10:10 AM	1.5	0.00	0.00	0.00	0.00	0.00	0.00
5/16/2007	10:25 AM	1.5	0.29	0.29	0.31	0.32	0.30	0.01
5/16/2007	10:45 AM	1.5	1.12	1.10	1.14	1.11	1.12	0.02
5/16/2007	11:15 AM	1.5	2.20	2.23	2.32	2.28	2.26	0.05
5/16/2007	11:45 AM	1.5	2.62	2.61	2.69	2.68	2.65	0.04
5/16/2007	12:15 PM	1.5	2.12	2.09	2.20	2.23	2.16	0.06
5/16/2007	1:15 PM	1.5	0.17	0.16	0.17	0.17	0.17	0.00
5/16/2007	2:00 PM	1.5	0.00	0.00	0.00	0.00	0.00	0.00
5/16/2007	2:45 PM	1.5	0.07	0.00	0.00	0.00	0.02	0.04
5/16/2007	3:20 PM	1.5	0.00	0.00	0.00	0.00	0.00	0.00
5/16/2007	3:35 PM	1.5	0.36	0.36	0.37	0.37	0.36	0.01
5/16/2007	4:00 PM	1.5	0.75	0.80	0.77	0.76	0.77	0.02
5/16/2007	4:30 PM	1.5	1.04	1.00	1.03	1.03	1.03	0.02
5/16/2007	5:00 PM	1.5	1.14	1.17	1.23	1.22	1.19	0.04
5/23/2007	8:55 AM	1.4	2.63	2.67	2.72	2.67	2.67	0.03
5/23/2007	9:10 AM	1.4	0.79	0.80	0.84	0.86	0.82	0.03
5/23/2007	9:30 AM	1.4	0.04	0.00	0.00	0.01	0.01	0.02
5/23/2007	10:10 AM	1.4	0.10	0.00	0.00	0.00	0.02	0.05
5/23/2007	10:25 AM	1.4	0.41	0.42	0.42	0.43	0.42	0.01
5/23/2007	10:45 AM	1.4	1.15	1.17	1.23	1.19	1.19	0.03
5/23/2007	11:15 AM	1.4	2.30	2.24	2.29	2.17	2.25	0.06
5/23/2007	11:45 AM	1.4	3.31	3.31	3.62	3.77	3.50	0.23
5/23/2007	12:15 PM	1.4	3.50	3.49	3.69	3.55	3.56	0.09
5/23/2007	1:00 PM	1.4	2.30	2.26	2.26	2.20	2.26	0.04
5/23/2007	2:15 PM	1.4	0.14	0.06	0.20	0.06	0.11	0.07
5/23/2007	3:20 PM	1.4	0.06	0.06	0.07	0.06	0.07	0.00
5/23/2007	3:35 PM	1.4	0.96	0.95	0.88	0.88	0.92	0.04

Date	Time	DO mg/L	Rep 1 NO_2^- (mg/L-N)	Rep 2 NO_2^- (mg/L-N)	Rep 3 NO_2^- (mg/L-N)	Rep 4 NO_2^- (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
5/23/2007	3:50 PM	1.4	1.68	1.72	1.86	1.84	1.78	0.09
5/23/2007	4:42 PM	1.4	3.81	3.72	3.79	3.75	3.77	0.04
5/23/2007	4:55 PM	1.4	2.95	3.08	2.73	2.70	2.87	0.18
5/31/2007	8:55 AM	1.3	0.24	0.25	0.25	0.26	0.25	0.01
5/31/2007	9:10 AM	1.3	0.25	0.26	0.21	0.22	0.23	0.02
5/31/2007	9:30 AM	1.3	0.00	0.09	0.00	0.00	0.02	0.05
5/31/2007	10:10 AM	1.3	0.00	0.00	0.00	0.00	0.00	0.00
5/31/2007	10:25 AM	1.3	0.06	0.01	0.01	0.09	0.04	0.04
5/31/2007	10:45 AM	1.3	0.45	0.49	0.48	0.54	0.49	0.04
5/31/2007	11:15 AM	1.3	1.52	1.51	1.52	1.74	1.57	0.11
5/31/2007	11:45 AM	1.3	2.67	2.63	2.60	2.62	2.63	0.03
5/31/2007	12:15 PM	1.3	3.24	3.14	3.35	3.29	3.25	0.09
5/31/2007	1:00 PM	1.3	3.57	3.59	3.50	3.56	3.56	0.04
5/31/2007	2:15 PM	1.3	0.23	0.12	0.08	0.08	0.13	0.07
5/31/2007	3:20 PM	1.3	0.05	0.04	0.04	0.05	0.04	0.01
5/31/2007	3:35 PM	1.3	0.60	0.60	0.62	0.63	0.61	0.01
5/31/2007	4:00 PM	1.3	1.27	1.24	1.26	1.26	1.26	0.01
5/31/2007	4:20 PM	1.3	1.62	1.58	1.56	1.61	1.59	0.03
5/31/2007	4:55 PM	1.3	1.95	1.95	1.97	2.00	1.97	0.02
6/20/2007	8:55 AM	1.2	0.00	0.00	N/A	N/A	0.00	0.00
6/20/2007	9:15 AM	1.2	0.00	0.00	N/A	N/A	0.00	0.00
6/20/2007	10:10 AM	1.2	0.00	0.00	N/A	N/A	0.00	0.00
6/20/2007	10:25 AM	1.2	0.00	0.00	N/A	N/A	0.00	0.00
6/20/2007	10:45 AM	1.2	0.22	0.22	N/A	N/A	0.22	0.00
6/20/2007	11:15 AM	1.2	0.79	0.79	N/A	N/A	0.79	0.01
6/20/2007	11:45 AM	1.2	1.29	1.27	N/A	N/A	1.28	0.01
6/20/2007	12:15 PM	1.2	1.38	1.38	N/A	N/A	1.38	0.00
6/20/2007	12:45 PM	1.2	1.08	1.05	N/A	N/A	1.07	0.03
6/20/2007	1:15 PM	1.2	0.12	0.12	N/A	N/A	0.12	0.00
6/20/2007	2:15 PM	1.2	0.02	0.01	N/A	N/A	0.01	0.00
6/20/2007	3:20 PM	1.2	0.00	0.00	N/A	N/A	0.00	0.00
6/20/2007	3:35 PM	1.2	0.84	0.86	N/A	N/A	0.85	0.01
6/20/2007	4:00 PM	1.2	2.14	2.11	N/A	N/A	2.12	0.03
6/20/2007	4:30 PM	1.2	0.22	0.23	N/A	N/A	0.22	0.00
6/20/2007	4:55 PM	1.2	0.00	0.00	N/A	N/A	0.00	0.00
7/9/2007	8:55 AM	1.1	0.00	0.01	0.00	0.00	0.00	0.00
7/9/2007	9:15 AM	1.1	0.00	0.03	0.01	0.00	0.01	0.01
7/9/2007	10:10 AM	1.1	0.00	0.00	0.00	0.01	0.00	0.00
7/9/2007	10:25 AM	1.1	0.01	0.09	0.01	0.00	0.03	0.04
7/9/2007	10:45 AM	1.1	0.04	0.04	0.05	0.02	0.04	0.01
7/9/2007	11:15 AM	1.1	0.76	0.75	0.75	0.79	0.76	0.02
7/9/2007	11:45 AM	1.1	1.61	1.67	1.59	1.57	1.61	0.04
7/9/2007	12:15 PM	1.1	2.43	2.45	2.52	2.41	2.45	0.05
7/9/2007	12:45 PM	1.1	2.96	2.90	2.80	2.84	2.88	0.07
7/9/2007	1:15 PM	1.1	0.69	0.72	0.66	0.66	0.68	0.03
7/9/2007	2:15 PM	1.1	0.05	0.05	0.05	0.06	0.05	0.00
7/9/2007	3:20 PM	1.1	0.02	0.01	0.01	0.06	0.03	0.02

Date	Time	DO mg/L	Rep 1 NO_2^- (mg/L-N)	Rep 2 NO_2^- (mg/L-N)	Rep 3 NO_2^- (mg/L-N)	Rep 4 NO_2^- (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
7/9/2007	3:35 PM	1.1	0.77	0.79	0.79	0.78	0.78	0.01
7/9/2007	4:00 PM	1.1	1.27	1.35	1.27	1.29	1.30	0.04
7/9/2007	4:30 PM	1.1	0.00	0.00	0.00	0.00	0.00	0.00
7/9/2007	4:55 PM	1.1	0.00	0.01	0.01	0.00	0.01	0.01
7/18/2007	8:55 AM	1.0	0.00	0.00	0.00	0.00	0.00	0.00
7/18/2007	9:15 AM	1.0	0.00	0.01	0.00	0.00	0.00	0.00
7/18/2007	10:10 AM	1.0	0.00	0.00	0.00	0.00	0.00	0.00
7/18/2007	10:25 AM	1.0	0.00	0.07	0.00	0.00	0.02	0.03
7/18/2007	10:45 AM	1.0	0.01	0.01	0.04	0.01	0.02	0.01
7/18/2007	11:15 AM	1.0	0.05	0.05	0.05	0.12	0.07	0.03
7/18/2007	11:45 AM	1.0	0.27	0.35	0.28	0.25	0.28	0.04
7/18/2007	12:15 PM	1.0	0.72	0.78	0.77	0.70	0.75	0.04
7/18/2007	12:45 PM	1.0	1.29	1.26	1.28	1.28	1.28	0.01
7/18/2007	1:15 PM	1.0	1.84	1.85	1.85	1.80	1.84	0.02
7/18/2007	2:15 PM	1.0	0.16	0.16	0.16	0.16	0.16	0.00
7/18/2007	3:20 PM	1.0	0.00	0.00	0.00	0.02	0.01	0.01
7/18/2007	3:35 PM	1.0	0.75	0.73	0.75	0.73	0.74	0.01
7/18/2007	4:00 PM	1.0	1.42	1.47	1.40	1.37	1.42	0.04
7/18/2007	4:30 PM	1.0	0.00	0.00	0.00	0.00	0.00	0.00
7/18/2007	4:55 PM	1.0	0.00	0.00	0.00	0.00	0.00	0.00
7/28/2007	8:55 AM	0.9	0.00	0.00	0.00	0.00	0.00	0.00
7/28/2007	9:15 AM	0.9	0.00	0.00	0.00	0.00	0.00	0.00
7/28/2007	10:10 AM	0.9	0.00	0.02	0.00	0.00	0.01	0.01
7/28/2007	10:25 AM	0.9	0.12	0.00	0.01	0.02	0.04	0.06
7/28/2007	10:45 AM	0.9	0.04	0.12	0.05	0.02	0.06	0.04
7/28/2007	11:15 AM	0.9	0.06	0.05	0.06	0.04	0.05	0.01
7/28/2007	11:45 AM	0.9	0.25	0.24	0.25	0.30	0.26	0.03
7/28/2007	12:15 PM	0.9	0.59	0.63	0.61	0.59	0.61	0.02
7/28/2007	12:45 PM	0.9	0.81	0.89	0.89	0.85	0.86	0.04
7/28/2007	1:15 PM	0.9	1.07	1.05	1.06	1.09	1.07	0.02
7/28/2007	2:15 PM	0.9	0.74	0.77	0.73	0.75	0.75	0.02
7/28/2007	3:20 PM	0.9	0.02	0.02	0.04	0.02	0.02	0.01
7/28/2007	3:35 PM	0.9	0.71	0.69	0.69	0.75	0.71	0.03
7/28/2007	4:00 PM	0.9	0.50	0.51	0.50	0.50	0.50	0.01
7/28/2007	4:30 PM	0.9	0.00	0.03	0.00	0.00	0.01	0.01
7/28/2007	4:55 PM	0.9	0.00	0.00	0.00	0.00	0.00	0.00
8/7/2007	8:55 AM	0.8	0.00	0.04	0.01	0.02	0.02	0.02
8/7/2007	9:15 AM	0.8	0.00	0.00	0.05	0.00	0.01	0.02
8/7/2007	10:10 AM	0.8	0.00	0.00	0.00	0.02	0.00	0.01
8/7/2007	10:25 AM	0.8	0.11	0.01	0.07	0.04	0.06	0.04
8/7/2007	10:45 AM	0.8	0.09	N/A	0.03	0.00	0.04	0.05
8/7/2007	11:15 AM	0.8	0.10	0.07	0.09	0.11	0.09	0.02
8/7/2007	11:45 AM	0.8	0.35	0.41	0.39	0.52	0.42	0.07
8/7/2007	12:15 PM	0.8	0.80	0.69	0.71	0.68	0.72	0.06
8/7/2007	12:45 PM	0.8	1.00	0.90	0.90	0.80	0.90	0.08
8/7/2007	1:15 PM	0.8	0.78	0.87	0.84	0.79	0.82	0.04
8/7/2007	2:15 PM	0.8	0.09	0.01	0.03	0.01	0.04	0.04

Date	Time	DO mg/L	Rep 1 NO_2^- (mg/L-N)	Rep 2 NO_2^- (mg/L-N)	Rep 3 NO_2^- (mg/L-N)	Rep 4 NO_2^- (mg/L-N)	Average (mg/L-N)	Standard Deviation (mg/L-N)
8/7/2007	3:20 PM	0.8	0.00	0.00	0.02	0.05	0.02	0.02
8/7/2007	3:35 PM	0.8	0.53	0.48	0.61	0.53	0.54	0.05
8/7/2007	4:00 PM	0.8	0.05	0.02	0.00	0.00	0.02	0.02
8/7/2007	4:30 PM	0.8	0.01	0.00	0.00	0.00	0.01	0.00
8/7/2007	4:55 PM	0.8	0.01	0.15	0.01	0.02	0.05	0.07
8/27/2007	8:55 AM	0.7	0.03	0.03	0.04	0.04	0.03	0.00
8/27/2007	9:15 AM	0.7	0.02	0.03	0.02	0.02	0.02	0.00
8/27/2007	10:10 AM	0.7	0.05	0.03	0.04	0.03	0.04	0.01
8/27/2007	10:25 AM	0.7	0.03	0.06	0.02	0.02	0.03	0.02
8/27/2007	10:45 AM	0.7	0.06	N/A	0.05	0.06	0.06	0.01
8/27/2007	11:15 AM	0.7	0.01	0.02	0.02	0.01	0.02	0.00
8/27/2007	11:45 AM	0.7	0.04	0.04	0.04	0.04	0.04	0.00
8/27/2007	12:15 PM	0.7	0.03	0.02	0.02	0.02	0.02	0.00
8/27/2007	1:00 PM	0.7	0.02	0.02	0.03	0.01	0.02	0.01
8/27/2007	1:45 PM	0.7	0.03	0.03	0.02	0.06	0.03	0.02
8/27/2007	2:30 PM	0.7	0.01	0.02	0.02	0.02	0.02	0.00
8/27/2007	3:20 PM	0.7	0.02	0.02	0.02	0.04	0.03	0.01
8/27/2007	3:35 PM	0.7	0.01	0.01	0.01	0.01	0.01	0.00
8/27/2007	4:00 PM	0.7	0.03	0.03	0.02	0.02	0.03	0.00
8/27/2007	4:30 PM	0.7	0.01	0.01	0.01	0.03	0.02	0.01
8/27/2007	4:55 PM	0.7	0.01	0.01	0.01	0.01	0.01	0.00

Table A-13: Cross cycle NO_3^- concentration data. Zero concentration indicates not detected.

Date	Time	DO	Rep 1 NO_3^- mg/L-N	Rep 2 NO_3^- mg/L-N	Average mg/L-N	Maximum- Average mg/L-N
3/20/2007	8:55 AM	1.7	0.00	0.00	0.00	0.0
3/20/2007	9:10 AM	1.7	0.00	0.00	0.00	0.0
3/20/2007	9:34 AM	1.7	0.00	0.00	0.00	0.0
3/20/2007	10:07 AM	1.7	0.00	0.00	0.00	0.0
3/20/2007	10:27 AM	1.7	0.00	0.00	0.00	0.0
3/20/2007	12:35 PM	1.7	2.08	2.10	2.09	0.0
3/20/2007	2:00 PM	1.7	2.75	2.80	2.78	0.0
3/20/2007	3:21 PM	1.7	2.57	2.52	2.54	0.0
3/20/2007	3:35 PM	1.7	1.22	1.25	1.23	0.0
3/20/2007	5:00 PM	1.7	0.17	0.16	0.16	0.0
3/22/2007	8:55 AM	1.7	0.00	0.00	0.00	0.0
3/22/2007	9:10 AM	1.7	0.00	0.00	0.00	0.0
3/22/2007	9:35 AM	1.7	0.00	0.00	0.00	0.0
3/22/2007	10:07 AM	1.7	0.00	0.00	0.00	0.0
3/22/2007	10:25 AM	1.7	0.53	0.53	0.53	0.0
3/22/2007	1:50 PM	1.7	3.92	3.95	3.94	0.0
3/22/2007	2:45 PM	1.7	4.20	4.19	4.19	0.0
3/22/2007	3:21 PM	1.7	4.05	4.01	4.03	0.0
3/22/2007	3:35 PM	1.7	3.03	3.04	3.03	0.0

Date	Time	DO	Rep 1 NO_3^- mg/L-N	Rep 2 NO_3^- mg/L-N	Average mg/L-N	Maximum- Average mg/L-N
3/22/2007	4:50 PM	1.7	0.10	0.09	0.10	0.0
4/20/2007	8:55 AM	2.0	0.10	0.17	0.13	0.0
4/20/2007	9:10 AM	2.0	0.03	0.06	0.05	0.0
4/20/2007	9:40 AM	2.0	0.01	0.18	0.09	0.1
4/20/2007	10:10 AM	2.0	0.20	0.21	0.20	0.0
4/20/2007	10:25 AM	2.0	0.13	0.00	0.07	0.1
4/20/2007	10:45 AM	2.0	0.60	0.57	0.59	0.0
4/20/2007	11:15 AM	2.0	0.41	0.42	0.41	0.0
4/20/2007	12:30 PM	2.0	3.57	3.54	3.55	0.0
4/20/2007	2:00 PM	2.0	4.64	4.63	4.63	0.0
4/20/2007	3:20 PM	2.0	5.01	4.96	4.99	0.0
4/20/2007	3:35 PM	2.0	3.68	3.69	3.69	0.0
4/20/2007	4:00 PM	2.0	1.91	1.89	1.90	0.0
4/20/2007	5:00 PM	2.0	0.12	0.12	0.12	0.0
4/30/2007	8:55 AM	1.8	0.84	0.84	0.84	0.0
4/30/2007	9:10 AM	1.8	0.00	0.00	0.00	0.0
4/30/2007	9:25 AM	1.8	0.00	0.00	0.00	0.0
4/30/2007	10:10 AM	1.8	0.00	0.00	0.00	0.0
4/30/2007	10:25 AM	1.8	0.00	0.00	0.00	0.0
4/30/2007	10:40 AM	1.8	0.00	0.00	0.00	0.0
4/30/2007	11:00 AM	1.8	0.00	0.00	0.00	0.0
4/30/2007	11:30 AM	1.8	0.73	0.73	0.73	0.0
4/30/2007	12:00 PM	1.8	2.41	2.32	2.36	0.0
4/30/2007	12:40 PM	1.8	5.48	5.50	5.49	0.0
4/30/2007	1:30 PM	1.8	7.10	7.12	7.11	0.0
4/30/2007	2:00 PM	1.8	7.27	7.20	7.23	0.0
4/30/2007	2:45 PM	1.8	7.60	7.57	7.59	0.0
4/30/2007	3:20 PM	1.8	7.68	7.65	7.67	0.0
4/30/2007	3:35 PM	1.8	6.41	6.42	6.42	0.0
4/30/2007	4:00 PM	1.8	4.32	4.31	4.31	0.0
4/30/2007	4:30 PM	1.8	1.98	1.86	1.92	0.1
4/30/2007	5:00 PM	1.8	0.43	0.42	0.43	0.0
5/8/2007	8:55 AM	1.6	3.27	3.29	3.28	0.0
5/8/2007	9:10 AM	1.6	0.08	0.00	0.04	0.0
5/8/2007	10:10 AM	1.6	0.00	0.00	0.00	0.0
5/8/2007	10:25 AM	1.6	0.11	0.13	0.12	0.0
5/8/2007	10:40 AM	1.6	0.29	0.31	0.30	0.0
5/8/2007	11:00 AM	1.6	0.72	0.75	0.73	0.0
5/8/2007	11:30 AM	1.6	2.86	2.90	2.88	0.0
5/8/2007	12:00 PM	1.6	4.60	4.67	4.64	0.0
5/8/2007	12:40 PM	1.6	9.24	9.18	9.21	0.0
5/8/2007	1:15 PM	1.6	9.97	9.72	9.85	0.1
5/8/2007	2:00 PM	1.6	9.81	9.94	9.87	0.1
5/8/2007	2:45 PM	1.6	10.03	10.02	10.02	0.0
5/8/2007	3:20 PM	1.6	10.15	10.19	10.17	0.0
5/8/2007	3:35 PM	1.6	9.13	9.15	9.14	0.0
5/8/2007	4:00 PM	1.6	7.42	7.45	7.44	0.0
5/8/2007	5:00 PM	1.6	3.72	3.72	3.72	0.0

Date	Time	DO	Rep 1 NO_3^- mg/L-N	Rep 2 NO_3^- mg/L-N	Average mg/L-N	Maximum- Average mg/L-N
5/16/2007	8:55 AM	1.5	2.39	2.53	2.46	0.1
5/16/2007	9:10 AM	1.5	0.08	0.07	0.08	0.0
5/16/2007	10:10 AM	1.5	0.03	0.03	0.03	0.0
5/16/2007	10:25 AM	1.5	0.11	0.11	0.11	0.0
5/16/2007	10:45 AM	1.5	0.22	0.22	0.22	0.0
5/16/2007	11:15 AM	1.5	0.61	0.62	0.61	0.0
5/16/2007	11:45 AM	1.5	1.87	1.86	1.87	0.0
5/16/2007	12:15 PM	1.5	4.73	4.74	4.74	0.0
5/16/2007	1:15 PM	1.5	10.09	10.17	10.13	0.0
5/16/2007	2:00 PM	1.5	10.89	10.79	10.84	0.0
5/16/2007	2:45 PM	1.5	11.25	10.00	10.63	0.6
5/16/2007	3:20 PM	1.5	11.43	11.58	11.51	0.1
5/16/2007	3:35 PM	1.5	10.21	10.25	10.23	0.0
5/16/2007	4:00 PM	1.5	7.95	7.92	7.93	0.0
5/16/2007	4:30 PM	1.5	5.74	5.73	5.74	0.0
5/16/2007	5:00 PM	1.5	3.82	3.82	3.82	0.0
5/23/2007	8:55 AM	1.4	0.18	0.17	0.18	0.0
5/23/2007	9:10 AM	1.4	0.10	0.10	0.10	0.0
5/23/2007	9:30 AM	1.4	0.12	0.10	0.11	0.0
5/23/2007	10:10 AM	1.4	0.13	0.14	0.13	0.0
5/23/2007	10:25 AM	1.4	0.15	0.14	0.14	0.0
5/23/2007	10:45 AM	1.4	0.34	0.33	0.33	0.0
5/23/2007	11:15 AM	1.4	0.33	0.32	0.33	0.0
5/23/2007	11:45 AM	1.4	0.88	0.88	0.88	0.0
5/23/2007	12:15 PM	1.4	2.30	2.33	2.31	0.0
5/23/2007	1:00 PM	1.4	5.12	5.14	5.13	0.0
5/23/2007	2:15 PM	1.4	7.50	7.47	7.48	0.0
5/23/2007	3:20 PM	1.4	7.52	7.80	7.66	0.1
5/23/2007	3:35 PM	1.4	6.05	6.01	6.03	0.0
5/23/2007	3:50 PM	1.4	4.45	4.44	4.44	0.0
5/23/2007	4:42 PM	1.4	0.43	0.42	0.43	0.0
5/23/2007	4:55 PM	1.4	0.18	0.19	0.19	0.0
5/31/2007	8:55 AM	1.3	0.73	0.64	0.69	0.0
5/31/2007	9:10 AM	1.3	0.06	0.06	0.06	0.0
5/31/2007	9:30 AM	1.3	0.16	0.19	0.18	0.0
5/31/2007	10:10 AM	1.3	0.39	0.40	0.40	0.0
5/31/2007	10:25 AM	1.3	0.10	N/A	0.10	0.0
5/31/2007	10:45 AM	1.3	0.31	0.25	0.28	0.0
5/31/2007	11:15 AM	1.3	0.34	0.33	0.34	0.0
5/31/2007	11:45 AM	1.3	0.69	0.66	0.67	0.0
5/31/2007	12:15 PM	1.3	1.11	1.18	1.14	0.0
5/31/2007	1:00 PM	1.3	2.57	2.61	2.59	0.0
5/31/2007	2:15 PM	1.3	7.08	7.10	7.09	0.0
5/31/2007	3:20 PM	1.3	7.69	7.52	7.60	0.1
5/31/2007	3:35 PM	1.3	6.76	6.80	6.78	0.0
5/31/2007	4:00 PM	1.3	4.74	4.79	4.77	0.0
5/31/2007	4:20 PM	1.3	2.99	3.02	3.01	0.0
5/31/2007	4:55 PM	1.3	0.98	0.97	0.98	0.0

Date	Time	DO	Rep 1 NO_3^- mg/L-N	Rep 2 NO_3^- mg/L-N	Average mg/L-N	Maximum- Average mg/L-N
6/14/2007	9:15 AM	1.2	0.21	0.17	0.19	0.0
6/14/2007	10:10 AM	1.2	0.10	0.10	0.10	0.0
6/14/2007	10:25 AM	1.2	0.07	0.07	0.07	0.0
6/14/2007	10:45 AM	1.2	0.10	0.04	0.07	0.0
6/14/2007	11:15 AM	1.2	0.03	0.04	0.04	0.0
6/14/2007	11:45 AM	1.2	0.02	0.03	0.03	0.0
6/14/2007	12:15 PM	1.2	0.08	0.09	0.09	0.0
6/14/2007	12:45 PM	1.2	0.07	0.10	0.09	0.0
6/14/2007	1:15 PM	1.2	0.08	0.11	0.10	0.0
6/14/2007	1:45 PM	1.2	N/A	N/A	N/A	N/A
6/14/2007	3:20 PM	1.2	N/A	N/A	N/A	N/A
6/14/2007	3:35 PM	1.2	N/A	N/A	N/A	N/A
6/14/2007	4:00 PM	1.2	N/A	N/A	N/A	N/A
6/14/2007	4:30 PM	1.2	N/A	N/A	N/A	N/A
6/14/2007	4:55 PM	1.2	N/A	N/A	N/A	N/A
6/20/2007	8:55 AM	1.2	0.07	0.06	0.07	0.0
6/20/2007	9:15 AM	1.2	0.09	0.04	0.07	0.0
6/20/2007	10:10 AM	1.2	0.04	0.11	0.07	0.0
6/20/2007	10:25 AM	1.2	0.11	0.09	0.10	0.0
6/20/2007	10:45 AM	1.2	0.09	0.05	0.07	0.0
6/20/2007	11:15 AM	1.2	0.14	0.17	0.16	0.0
6/20/2007	11:45 AM	1.2	0.56	0.58	0.57	0.0
6/20/2007	12:15 PM	1.2	1.64	1.58	1.61	0.0
6/20/2007	12:45 PM	1.2	3.20	3.20	3.20	0.0
6/20/2007	1:15 PM	1.2	4.30	4.32	4.31	0.0
6/20/2007	2:15 PM	1.2	4.38	4.41	4.39	0.0
6/20/2007	3:20 PM	1.2	4.38	4.37	4.37	0.0
6/20/2007	3:35 PM	1.2	3.01	2.96	2.98	0.0
6/20/2007	4:00 PM	1.2	0.46	0.41	0.43	0.0
6/20/2007	4:30 PM	1.2	0.09	0.10	0.09	0.0
6/20/2007	4:55 PM	1.2	0.07	0.07	0.07	0.0
7/9/2007	8:55 AM	1.1	0.11	0.20	0.15	0.0
7/9/2007	9:15 AM	1.1	0.07	0.10	0.08	0.0
7/9/2007	10:10 AM	1.1	0.06	0.09	0.07	0.0
7/9/2007	10:25 AM	1.1	0.06	0.09	0.08	0.0
7/9/2007	10:45 AM	1.1	0.05	0.10	0.08	0.0
7/9/2007	11:15 AM	1.1	0.18	0.13	0.16	0.0
7/9/2007	11:45 AM	1.1	0.30	0.31	0.30	0.0
7/9/2007	12:15 PM	1.1	0.77	2.37	1.57	0.8
7/9/2007	12:45 PM	1.1	1.90	1.91	1.91	0.0
7/9/2007	1:15 PM	1.1	4.05	4.10	4.07	0.0
7/9/2007	2:15 PM	1.1	4.41	4.42	4.42	0.0
7/9/2007	3:20 PM	1.1	4.50	4.50	4.50	0.0
7/9/2007	3:35 PM	1.1	2.63	2.67	2.65	0.0
7/9/2007	4:00 PM	1.1	0.25	0.21	0.23	0.0
7/9/2007	4:30 PM	1.1	0.07	0.10	0.09	0.0
7/9/2007	4:55 PM	1.1	0.07	0.16	0.12	0.0
7/18/2007	8:55 AM	1.0	0.14	0.10	0.12	0.0

Date	Time	DO	Rep 1 NO_3^- mg/L-N	Rep 2 NO_3^- mg/L-N	Average mg/L-N	Maximum- Average mg/L-N
7/18/2007	9:15 AM	1.0	0.24	0.75	0.49	0.3
7/18/2007	10:10 AM	1.0	0.16	0.12	0.14	0.0
7/18/2007	10:25 AM	1.0	0.18	0.19	0.18	0.0
7/18/2007	10:45 AM	1.0	0.15	0.15	0.15	0.0
7/18/2007	11:15 AM	1.0	0.33	0.29	0.31	0.0
7/18/2007	11:45 AM	1.0	0.13	0.10	0.11	0.0
7/18/2007	12:15 PM	1.0	0.22	0.28	0.25	0.0
7/18/2007	12:45 PM	1.0	0.54	0.58	0.56	0.0
7/18/2007	1:15 PM	1.0	1.17	1.34	1.26	0.1
7/18/2007	2:15 PM	1.0	3.94	3.91	3.93	0.0
7/18/2007	3:20 PM	1.0	3.99	3.96	3.98	0.0
7/18/2007	3:35 PM	1.0	2.34	2.36	2.35	0.0
7/18/2007	4:00 PM	1.0	0.27	0.19	0.23	0.0
7/18/2007	4:30 PM	1.0	0.03	0.05	0.04	0.0
7/18/2007	4:55 PM	1.0	0.10	0.12	0.11	0.0
7/28/2007	8:55 AM	0.9	1.29	1.00	1.14	0.1
7/28/2007	9:15 AM	0.9	0.05	0.06	0.05	0.0
7/28/2007	10:10 AM	0.9	0.06	0.03	0.05	0.0
7/28/2007	10:25 AM	0.9	0.07	0.32	0.19	0.1
7/28/2007	10:45 AM	0.9	0.22	0.13	0.17	0.0
7/28/2007	11:15 AM	0.9	0.16	0.42	0.29	0.1
7/28/2007	11:45 AM	0.9	0.07	0.07	0.07	0.0
7/28/2007	12:15 PM	0.9	0.41	0.20	0.31	0.1
7/28/2007	12:45 PM	0.9	0.06	0.53	0.30	0.2
7/28/2007	1:15 PM	0.9	0.87	0.74	0.81	0.1
7/28/2007	2:15 PM	0.9	2.41	2.37	2.39	0.0
7/28/2007	3:20 PM	0.9	3.08	3.15	3.11	0.0
7/28/2007	3:35 PM	0.9	1.67	1.53	1.60	0.1
7/28/2007	4:00 PM	0.9	0.33	0.40	0.37	0.0
7/28/2007	4:30 PM	0.9	0.07	0.09	0.08	0.0
7/28/2007	4:55 PM	0.9	0.04	0.08	0.06	0.0
8/8/2007	8:55 AM	0.8	0.08	0.06	0.07	0.0
8/8/2007	9:15 AM	0.8	0.04	0.04	0.04	0.0
8/8/2007	10:10 AM	0.8	0.14	0.13	0.14	0.0
8/8/2007	10:25 AM	0.8	0.03	0.02	0.03	0.0
8/8/2007	10:45 AM	0.8	0.08	0.06	0.07	0.0
8/8/2007	11:15 AM	0.8	0.04	0.04	0.04	0.0
8/8/2007	11:45 AM	0.8	0.13	0.13	0.13	0.0
8/8/2007	12:15 PM	0.8	0.30	0.29	0.30	0.0
8/8/2007	12:45 PM	0.8	0.72	0.72	0.72	0.0
8/8/2007	1:15 PM	0.8	1.55	1.54	1.54	0.0
8/8/2007	2:15 PM	0.8	2.39	2.38	2.38	0.0
8/8/2007	3:20 PM	0.8	2.38	2.37	2.37	0.0
8/8/2007	3:35 PM	0.8	0.98	0.98	0.98	0.0
8/8/2007	4:00 PM	0.8	0.04	0.03	0.04	0.0
8/8/2007	4:30 PM	0.8	0.36	0.37	0.37	0.0
8/8/2007	4:55 PM	0.8	0.04	0.03	0.04	0.0
8/27/2007	8:55 AM	0.7	0.04	0.04	0.04	0.0

Date	Time	DO	Rep 1 NO_3^- mg/L-N	Rep 2 NO_3^- mg/L-N	Average mg/L-N	Maximum- Average mg/L-N
8/27/2007	9:15 AM	0.7	0.02	0.04	0.03	0.0
8/27/2007	10:10 AM	0.7	0.17	0.17	0.17	0.0
8/27/2007	10:25 AM	0.7	0.08	0.09	0.08	0.0
8/27/2007	10:45 AM	0.7	0.05	0.01	0.03	0.0
8/27/2007	11:15 AM	0.7	0.03	0.02	0.03	0.0
8/27/2007	11:45 AM	0.7	0.03	0.03	0.03	0.0
8/27/2007	12:15 PM	0.7	0.02	0.02	0.02	0.0
8/27/2007	1:00 PM	0.7	0.02	N/A	0.02	0.0
8/27/2007	1:45 PM	0.7	0.18	0.16	0.17	0.0
8/27/2007	2:30 PM	0.7	0.21	0.21	0.21	0.0
8/27/2007	3:20 PM	0.7	0.16	0.15	0.15	0.0
8/27/2007	3:35 PM	0.7	0.00	N/A	0.00	0.0
8/27/2007	4:00 PM	0.7	0.16	0.15	0.15	0.0
8/27/2007	4:30 PM	0.7	0.06	0.06	0.06	0.0
8/27/2007	4:55 PM	0.7	0.03	0.04	0.03	0.0

Table A-14: Cross cycle soluble chemical oxygen demand (SCOD) concentrations.

Date	Time	DO (mg/L)	Rep 1 SCOD (mg/L)	Rep 2 SCOD (mg/L)	Average SCOD (mg/L)	Maximum-Average (mg/L)
3/20/2007	8:55 AM	1.7	859	843	851	8
3/20/2007	9:10 AM	1.7	914	914	914	0
3/20/2007	9:34 AM	1.7	937	937	937	0
3/20/2007	10:07 AM	1.7	976	953	965	12
3/20/2007	12:35 PM	1.7	890	890	890	0
3/20/2007	2:00 PM	1.7	867	867	867	0
3/20/2007	3:21 PM	1.7	851	835	843	8
3/20/2007	3:35 PM	1.7	671	600	635	35
3/20/2007	5:00 PM	1.7	875	867	871	4
3/22/2007	8:55 AM	1.7	804	804	804	0
3/22/2007	9:10 AM	1.7	890	890	890	0
3/22/2007	9:35 AM	1.7	859	867	863	4
3/22/2007	10:07 AM	1.7	851	867	859	8
3/22/2007	10:25 AM	1.7	890	859	875	16
3/22/2007	1:50 PM	1.7	796	804	800	4
3/22/2007	2:45 PM	1.7	804	788	796	8
3/22/2007	3:21 PM	1.7	788	788	788	0
3/22/2007	3:35 PM	1.7	780	780	780	0
3/22/2007	4:50 PM	1.7	788	780	784	4
4/20/2007	8:55 AM	2.0	720	736	728	8
4/20/2007	9:10 AM	2.0	775	775	775	0
4/20/2007	9:40 AM	2.0	767	799	783	16
4/20/2007	10:10 AM	2.0	767	775	771	4
4/20/2007	10:25 AM	2.0	775	791	783	8
4/20/2007	10:45 AM	2.0	767	751	759	8
4/20/2007	11:15 AM	2.0	759	736	748	12
4/20/2007	12:30 PM	2.0	736	744	740	4
4/20/2007	2:00 PM	2.0	720	720	720	0
4/20/2007	3:20 PM	2.0	704	712	708	4
4/20/2007	3:35 PM	2.0	696	696	696	0
4/20/2007	4:00 PM	2.0	712	712	712	0
4/20/2007	5:00 PM	2.0	728	712	720	8
4/30/2007	8:55 AM	1.8	714	760	737	23
4/30/2007	9:10 AM	1.8	852	714	783	69
4/30/2007	9:25 AM	1.8	745	714	729	15
4/30/2007	10:10 AM	1.8	729	729	729	0
4/30/2007	10:25 AM	1.8	729	745	737	8
4/30/2007	10:40 AM	1.8	791	867	829	38
4/30/2007	11:00 AM	1.8	837	837	837	0
4/30/2007	11:30 AM	1.8	760	714	737	23
4/30/2007	12:00 PM	1.8	791	775	783	8
4/30/2007	12:40 PM	1.8	760	714	737	23
4/30/2007	1:30 PM	1.8	806	913	860	54
4/30/2007	2:00 PM	1.8	791	745	768	23
4/30/2007	2:45 PM	1.8	821	821	821	0
4/30/2007	3:20 PM	1.8	837	760	798	38

Date	Time	DO (mg/L)	Rep 1 SCOD (mg/L)	Rep 2 SCOD (mg/L)	Average SCOD (mg/L)	Maximum-Average (mg/L)
4/30/2007	3:35 PM	1.8	699	729	714	15
4/30/2007	4:00 PM	1.8	699	714	706	8
4/30/2007	4:30 PM	1.8	775	729	752	23
4/30/2007	5:00 PM	1.8	699	684	691	8
5/8/2007	8:55 AM	1.6	603	595	599	4
5/8/2007	9:10 AM	1.6	722	722	722	0
5/8/2007	10:10 AM	1.6	706	698	702	4
5/8/2007	10:25 AM	1.6	682	674	678	4
5/8/2007	10:40 AM	1.6	666	658	662	4
5/8/2007	11:00 AM	1.6	650	658	654	4
5/8/2007	11:30 AM	1.6	658	634	646	12
5/8/2007	12:00 PM	1.6	642	634	638	4
5/8/2007	12:40 PM	1.6	626	611	619	8
5/8/2007	1:15 PM	1.6	603	611	607	4
5/8/2007	2:00 PM	1.6	642	642	642	0
5/8/2007	2:45 PM	1.6	603	587	595	8
5/8/2007	3:20 PM	1.6	603	642	622	20
5/8/2007	3:35 PM	1.6	603	595	599	4
5/8/2007	4:00 PM	1.6	603	603	603	0
5/8/2007	5:00 PM	1.6	603	603	603	0
5/16/2007	8:55 AM	1.5	523	523	523	0
5/16/2007	9:10 AM	1.5	642	603	622	20
5/16/2007	10:10 AM	1.5	603	603	603	0
5/16/2007	10:25 AM	1.5	587	579	583	4
5/16/2007	10:45 AM	1.5	563	579	571	8
5/16/2007	11:15 AM	1.5	563	595	579	16
5/16/2007	11:45 AM	1.5	555	539	547	8
5/16/2007	12:15 PM	1.5	547	547	547	0
5/16/2007	1:15 PM	1.5	563	563	563	0
5/16/2007	2:00 PM	1.5	531	531	531	0
5/16/2007	2:45 PM	1.5	547	555	551	4
5/16/2007	3:20 PM	1.5	555	539	547	8
5/16/2007	3:35 PM	1.5	547	539	543	4
5/16/2007	4:00 PM	1.5	540	531	536	4
5/16/2007	4:30 PM	1.5	523	523	523	0
5/16/2007	5:00 PM	1.5	555	571	563	8
5/23/2007	8:55 AM	1.4	788	788	788	0
5/23/2007	9:10 AM	1.4	899	899	899	0
5/23/2007	9:30 AM	1.4	923	827	875	48
5/23/2007	10:10 AM	1.4	883	875	879	4
5/23/2007	10:25 AM	1.4	859	859	859	0
5/23/2007	10:45 AM	1.4	811	811	811	0
5/23/2007	12:15 PM	1.4	804	804	804	0
5/23/2007	1:00 PM	1.4	819	835	827	8
5/23/2007	2:15 PM	1.4	835	819	827	8
5/23/2007	3:20 PM	1.4	796	788	792	4
5/23/2007	3:35 PM	1.4	780	780	780	0
5/23/2007	3:50 PM	1.4	780	780	780	0

Date	Time	DO (mg/L)	Rep 1 SCOD (mg/L)	Rep 2 SCOD (mg/L)	Average SCOD (mg/L)	Maximum-Average (mg/L)
5/23/2007	4:42 PM	1.4	780	780	780	0
5/23/2007	4:55 PM	1.4	804	819	811	8
5/31/2007	8:55 AM	1.3	780	700	740	40
5/31/2007	9:10 AM	1.3	851	851	851	0
5/31/2007	9:30 AM	1.3	819	819	819	0
5/31/2007	10:10 AM	1.3	811	819	815	4
5/31/2007	10:25 AM	1.3	819	811	815	4
5/31/2007	10:45 AM	1.3	756	740	748	8
5/31/2007	11:15 AM	1.3	764	764	764	0
5/31/2007	11:45 AM	1.3	756	748	752	4
5/31/2007	12:15 PM	1.3	764	756	760	4
5/31/2007	1:00 PM	1.3	780	748	764	16
5/31/2007	2:15 PM	1.3	756	748	752	4
5/31/2007	3:20 PM	1.3	748	780	764	16
5/31/2007	3:35 PM	1.3	788	740	764	24
5/31/2007	4:00 PM	1.3	740	756	748	8
5/31/2007	4:20 PM	1.3	740	732	736	4
5/31/2007	4:55 PM	1.3	732	724	728	4
6/14/2007	9:15 AM	1.2	1062	1062	1062	0
6/14/2007	10:10 AM	1.2	1007	1031	1019	12
6/14/2007	10:25 AM	1.2	1101	1070	1085	16
6/14/2007	10:45 AM	1.2	1031	1031	1031	0
6/14/2007	11:15 AM	1.2	1023	976	1000	23
6/14/2007	11:45 AM	1.2	992	1031	1011	20
6/14/2007	12:15 PM	1.2	1015	992	1003	12
6/14/2007	12:45 PM	1.2	992	968	980	12
6/14/2007	1:15 PM	1.2	961	914	937	23
6/14/2007	1:45 PM	1.2	945	976	961	16
6/14/2007	3:20 PM	1.2	945	945	945	0
6/14/2007	3:35 PM	1.2	945	953	949	4
6/14/2007	4:00 PM	1.2	984	984	984	0
6/14/2007	4:30 PM	1.2	968	984	976	8
6/14/2007	4:55 PM	1.2	1007	992	1000	8
6/20/2007	8:55 AM	1.2	917	917	917	0
6/20/2007	9:15 AM	1.2	972	996	984	12
6/20/2007	10:10 AM	1.2	956	948	952	4
6/20/2007	10:25 AM	1.2	933	933	933	0
6/20/2007	10:45 AM	1.2	933	956	944	12
6/20/2007	11:15 AM	1.2	933	917	925	8
6/20/2007	11:45 AM	1.2	909	893	901	8
6/20/2007	12:15 PM	1.2	909	909	909	0
6/20/2007	12:45 PM	1.2	877	877	877	0
6/20/2007	1:15 PM	1.2	893	885	889	4
6/20/2007	2:15 PM	1.2	901	877	889	12
6/20/2007	3:20 PM	1.2	861	854	858	4
6/20/2007	3:35 PM	1.2	877	877	877	0
6/20/2007	4:00 PM	1.2	861	869	865	4
6/20/2007	4:30 PM	1.2	885	885	885	0

Date	Time	DO (mg/L)	Rep 1 SCOD (mg/L)	Rep 2 SCOD (mg/L)	Average SCOD (mg/L)	Maximum-Average (mg/L)
6/20/2007	4:55 PM	1.2	877	877	877	0
7/9/2007	8:55 AM	1.1	571	586	579	8
7/9/2007	9:15 AM	1.1	641	641	641	0
7/9/2007	10:10 AM	1.1	618	610	614	4
7/9/2007	10:25 AM	1.1	571	547	559	12
7/9/2007	10:45 AM	1.1	563	571	567	4
7/9/2007	11:15 AM	1.1	563	579	571	8
7/9/2007	11:45 AM	1.1	571	579	575	4
7/9/2007	12:15 PM	1.1	540	532	536	4
7/9/2007	12:45 PM	1.1	540	540	540	0
7/9/2007	1:15 PM	1.1	540	532	536	4
7/9/2007	2:15 PM	1.1	540	540	540	0
7/9/2007	3:20 PM	1.1	524	524	524	0
7/9/2007	3:35 PM	1.1	524	540	532	8
7/9/2007	4:30 PM	1.1	524	524	524	0
7/9/2007	4:55 PM	1.1	524	524	524	0
7/18/2007	8:55 AM	1.0	516	516	516	0
7/18/2007	9:15 AM	1.0	594	602	598	4
7/18/2007	10:25 AM	1.0	688	703	695	8
7/18/2007	10:45 AM	1.0	656	563	610	47
7/18/2007	11:15 AM	1.0	579	579	579	0
7/18/2007	11:45 AM	1.0	571	594	582	12
7/18/2007	12:15 PM	1.0	516	516	516	0
7/18/2007	12:45 PM	1.0	586	586	586	0
7/18/2007	1:15 PM	1.0	563	501	532	31
7/18/2007	2:15 PM	1.0	524	501	512	12
7/18/2007	3:20 PM	1.0	485	462	474	12
7/18/2007	3:35 PM	1.0	493	485	489	4
7/18/2007	4:00 PM	1.0	493	485	489	4
7/18/2007	4:30 PM	1.0	501	509	505	4
7/18/2007	4:55 PM	1.0	501	485	493	8
7/28/2007	8:55 AM	0.9	577	561	569	8
7/28/2007	9:15 AM	0.9	713	681	697	16
7/28/2007	10:10 AM	0.9	649	633	641	8
7/28/2007	10:25 AM	0.9	649	625	637	12
7/28/2007	10:45 AM	0.9	609	593	601	8
7/28/2007	11:15 AM	0.9	625	625	625	0
7/28/2007	11:45 AM	0.9	625	609	617	8
7/28/2007	12:15 PM	0.9	577	577	577	0
7/28/2007	12:45 PM	0.9	577	561	569	8
7/28/2007	1:15 PM	0.9	553	553	553	0
7/28/2007	2:15 PM	0.9	545	553	549	4
7/28/2007	3:20 PM	0.9	577	561	569	8
7/28/2007	3:35 PM	0.9	553	545	549	4
7/28/2007	4:00 PM	0.9	537	N/A	537	0
7/28/2007	4:30 PM	0.9	529	537	533	4
7/28/2007	4:55 PM	0.9	545	537	541	4
8/7/2007	8:55 AM	0.8	553	593	573	20

Date	Time	DO (mg/L)	Rep 1 SCOD (mg/L)	Rep 2 SCOD (mg/L)	Average SCOD (mg/L)	Maximum-Average (mg/L)
8/7/2007	9:15 AM	0.8	649	N/A	649	0
8/7/2007	10:10 AM	0.8	633	633	633	0
8/7/2007	10:25 AM	0.8	649	625	637	12
8/7/2007	10:45 AM	0.8	625	N/A	625	0
8/7/2007	11:15 AM	0.8	617	593	605	12
8/7/2007	11:45 AM	0.8	577	561	569	8
8/7/2007	12:15 PM	0.8	553	553	553	0
8/7/2007	12:45 PM	0.8	553	553	553	0
8/7/2007	1:15 PM	0.8	561	553	557	4
8/7/2007	2:15 PM	0.8	577	553	565	12
8/7/2007	3:20 PM	0.8	561	545	553	8
8/7/2007	3:35 PM	0.8	553	553	553	0
8/7/2007	4:00 PM	0.8	545	537	541	4
8/7/2007	4:30 PM	0.8	553	N/A	553	0
8/7/2007	4:55 PM	0.8	561	N/A	553	0
8/27/2007	8:55 AM	0.7	1332	1316	1324	8
8/27/2007	9:15 AM	0.7	1453	1429	1441	12
8/27/2007	10:10 AM	0.7	1453	1462	1458	4
8/27/2007	10:25 AM	0.7	1453	1445	1449	4
8/27/2007	10:45 AM	0.7	1453	1453	1453	0
8/27/2007	11:15 AM	0.7	1405	1405	1405	0
8/27/2007	11:45 AM	0.7	1413	1397	1405	8
8/27/2007	12:15 PM	0.7	1389	1373	1381	8
8/27/2007	1:00 PM	0.7	1381	1332	1356	24
8/27/2007	1:45 PM	0.7	1364	1356	1360	4
8/27/2007	2:30 PM	0.7	1373	1373	1373	0
8/27/2007	3:20 PM	0.7	1356	1348	1352	4
8/27/2007	3:35 PM	0.7	1340	1324	1332	8
8/27/2007	4:00 PM	0.7	1332	1332	1332	0
8/27/2007	4:30 PM	0.7	1340	1324	1332	8
8/27/2007	4:55 PM	0.7	1340	1373	1356	16

Table A-15: Cross cycle acetic acid chemical oxygen demand (COD) concentrations.

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
3/20/2007	8:55 AM	1.7	21	25	26	26	24	2
3/20/2007	9:10 AM	1.7	24	26	26	26	25	1
3/20/2007	9:34 AM	1.7	25	26	25	26	26	1
3/20/2007	10:07 AM	1.7	25	27	26	25	26	1
3/20/2007	10:27 AM	1.7	24	25	24	25	25	1
3/20/2007	12:35 PM	1.7	28	27	26	28	27	1
3/20/2007	2:00 PM	1.7	29	27	28	28	28	1
3/20/2007	3:21 PM	1.7	31	29	28	30	30	1
3/20/2007	3:35 PM	1.7	35	33	34	35	34	1
3/20/2007	5:00 PM	1.7	28	29	30	30	29	1

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
3/22/2007	8:55 AM	1.7	30	30	30	30	30	0
3/22/2007	9:10 AM	1.7	41	39	40	39	40	1
3/22/2007	9:35 AM	1.7	29	29	30	30	29	1
3/22/2007	10:07 AM	1.7	29	29	29	N/A	29	0
3/22/2007	10:25 AM	1.7	29	29	29	N/A	29	0
3/22/2007	1:50 PM	1.7	30	30	30	30	30	0
3/22/2007	2:45 PM	1.7	32	31	32	33	32	1
3/22/2007	3:21 PM	1.7	31	33	31	32	32	1
3/22/2007	3:35 PM	1.7	32	33	33	34	33	1
3/22/2007	4:50 PM	1.7	32	33	32	33	33	1
4/20/2007	8:55 AM	2.0	20	20	21	20	20	0
4/20/2007	9:10 AM	2.0	20	20	19	19	20	0
4/20/2007	9:40 AM	2.0	19	19	19	19	19	0
4/20/2007	10:10 AM	2.0	19	19	19	18	19	0
4/20/2007	10:25 AM	2.0	19	19	18	18	18	0
4/20/2007	10:45 AM	2.0	17	19	19	18	18	1
4/20/2007	11:15 AM	2.0	19	19	19	18	19	0
4/20/2007	12:30 PM	2.0	19	18	19	18	19	1
4/20/2007	2:00 PM	2.0	21	22	20	21	21	1
4/20/2007	3:20 PM	2.0	21	21	23	22	22	1
4/20/2007	3:35 PM	2.0	22	21	20	20	21	1
4/20/2007	4:00 PM	2.0	21	21	20	20	20	1
4/20/2007	5:00 PM	2.0	20	20	19	19	19	0
4/30/2007	8:55 AM	1.8	19	20	20	20	20	1
4/30/2007	9:10 AM	1.8	24	23	23	22	23	1
4/30/2007	9:25 AM	1.8	16	19	20	20	19	2
4/30/2007	10:10 AM	1.8	19	19	18	21	19	1
4/30/2007	10:25 AM	1.8	22	21	22	21	21	1
4/30/2007	10:40 AM	1.8	20	21	19	21	20	1
4/30/2007	11:00 AM	1.8	15	21	22	20	19	3
4/30/2007	11:30 AM	1.8	23	21	20	22	21	1
4/30/2007	12:00 PM	1.8	21	22	20	21	21	1
4/30/2007	12:40 PM	1.8	22	23	22	21	22	1
4/30/2007	1:30 PM	1.8	23	23	22	24	23	1
4/30/2007	2:00 PM	1.8	23	22	22	22	22	0
4/30/2007	2:45 PM	1.8	23	23	23	24	23	1
4/30/2007	3:20 PM	1.8	20	22	24	24	22	2
4/30/2007	3:35 PM	1.8	23	23	23	23	23	0
4/30/2007	4:00 PM	1.8	24	20	24	23	23	2
4/30/2007	4:30 PM	1.8	23	24	25	25	24	1
4/30/2007	5:00 PM	1.8	24	22	23	23	23	1
5/8/2007	8:55 AM	1.6	17	18	N/A	N/A	18	0
5/8/2007	9:10 AM	1.6	24	22	N/A	N/A	23	1
5/8/2007	10:10 AM	1.6	15	14	N/A	N/A	15	0
5/8/2007	10:25 AM	1.6	15	14	N/A	N/A	15	0
5/8/2007	10:40 AM	1.6	14	14	N/A	N/A	14	0
5/8/2007	11:00 AM	1.6	13	13	N/A	N/A	13	0

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
5/8/2007	11:30 AM	1.6	13	12	N/A	N/A	12	1
5/8/2007	12:00 PM	1.6	11	11	N/A	N/A	11	0
5/8/2007	12:40 PM	1.6	10	10	N/A	N/A	10	0
5/8/2007	1:15 PM	1.6	9	8	N/A	N/A	8	1
5/8/2007	2:00 PM	1.6	7	7	N/A	N/A	7	0
5/8/2007	2:45 PM	1.6	6	5	N/A	N/A	5	1
5/8/2007	3:20 PM	1.6	4	3	N/A	N/A	4	0
5/8/2007	3:35 PM	1.6	3	3	N/A	N/A	3	0
5/8/2007	4:00 PM	1.6	3	3	N/A	N/A	3	0
5/8/2007	5:00 PM	1.6	2	N/A	N/A	N/A	2	0
5/16/2007	8:55 AM	1.5	18	16	N/A	N/A	17	1
5/16/2007	9:10 AM	1.5	37	36	N/A	N/A	36	0
5/16/2007	10:10 AM	1.5	18	18	N/A	N/A	18	0
5/16/2007	10:25 AM	1.5	18	18	N/A	N/A	18	0
5/16/2007	10:45 AM	1.5	19	18	N/A	N/A	19	0
5/16/2007	11:15 AM	1.5	18	18	N/A	N/A	18	0
5/16/2007	11:45 AM	1.5	19	19	N/A	N/A	19	0
5/16/2007	12:15 PM	1.5	19	20	N/A	N/A	20	0
5/16/2007	1:15 PM	1.5	18	17	N/A	N/A	18	1
5/16/2007	2:00 PM	1.5	18	18	N/A	N/A	18	0
5/16/2007	2:45 PM	1.5	19	20	N/A	N/A	20	0
5/16/2007	3:20 PM	1.5	20	19	N/A	N/A	20	0
5/16/2007	4:00 PM	1.5	21	20	N/A	N/A	20	0
5/16/2007	4:30 PM	1.5	20	19	N/A	N/A	19	0
5/16/2007	5:00 PM	1.5	19	19	N/A	N/A	19	0
5/23/2007	8:55 AM	1.4	21	23	N/A	N/A	22	1
5/23/2007	9:10 AM	1.4	61	61	N/A	N/A	61	0
5/23/2007	9:30 AM	1.4	29	28	N/A	N/A	28	0
5/23/2007	10:10 AM	1.4	27	26	N/A	N/A	26	0
5/23/2007	10:25 AM	1.4	25	25	N/A	N/A	25	0
5/23/2007	10:45 AM	1.4	22	22	N/A	N/A	22	0
5/23/2007	11:15 AM	1.4	23	23	N/A	N/A	23	0
5/23/2007	11:45 AM	1.4	26	25	N/A	N/A	25	1
5/23/2007	12:15 PM	1.4	25	26	N/A	N/A	25	0
5/23/2007	1:00 PM	1.4	25	55	N/A	N/A	40	15
5/23/2007	2:15 PM	1.4	32	27	N/A	N/A	30	2
5/23/2007	3:20 PM	1.4	25	23	N/A	N/A	24	1
5/23/2007	3:35 PM	1.4	24	23	N/A	N/A	24	1
5/23/2007	3:50 PM	1.4	22	22	N/A	N/A	22	0
5/23/2007	4:42 PM	1.4	22	22	N/A	N/A	22	0
5/23/2007	4:55 PM	1.4	22	22	N/A	N/A	22	0
5/31/2007	8:55 AM	1.3	23	23	N/A	N/A	23	0
5/31/2007	9:10 AM	1.3	55	57	N/A	N/A	56	1
5/31/2007	9:30 AM	1.3	23	25	N/A	N/A	24	1
5/31/2007	10:10 AM	1.3	22	22	N/A	N/A	22	0
5/31/2007	10:25 AM	1.3	21	19	N/A	N/A	20	1
5/31/2007	10:45 AM	1.3	21	21	N/A	N/A	21	0

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
5/31/2007	11:15 AM	1.3	24	22	N/A	N/A	23	1
5/31/2007	11:45 AM	1.3	22	21	N/A	N/A	21	0
5/31/2007	12:15 PM	1.3	24	20	N/A	N/A	22	2
5/31/2007	1:00 PM	1.3	24	22	N/A	N/A	23	1
5/31/2007	2:15 PM	1.3	24	24	N/A	N/A	24	0
5/31/2007	3:20 PM	1.3	25	25	N/A	N/A	25	0
5/31/2007	3:35 PM	1.3	24	24	N/A	N/A	24	0
5/31/2007	4:00 PM	1.3	24	24	N/A	N/A	24	0
5/31/2007	4:20 PM	1.3	23	23	N/A	N/A	23	0
5/31/2007	4:55 PM	1.3	22	22	N/A	N/A	22	0
6/14/2007	9:15 AM	1.2	39	39	N/A	N/A	39	0
6/14/2007	10:10 AM	1.2	20	20	N/A	N/A	20	0
6/14/2007	10:25 AM	1.2	19	19	N/A	N/A	19	0
6/14/2007	10:45 AM	1.2	19	19	N/A	N/A	19	0
6/14/2007	11:15 AM	1.2	19	19	N/A	N/A	19	0
6/14/2007	11:45 AM	1.2	18	19	N/A	N/A	18	0
6/14/2007	12:15 PM	1.2	18	20	N/A	N/A	19	1
6/14/2007	12:45 PM	1.2	20	17	N/A	N/A	19	1
6/14/2007	1:15 PM	1.2	19	19	N/A	N/A	19	0
6/14/2007	1:45 PM	1.2	15	14	N/A	N/A	14	0
6/14/2007	3:20 PM	1.2	21	22	N/A	N/A	22	0
6/14/2007	3:35 PM	1.2	23	20	N/A	N/A	21	1
6/14/2007	4:00 PM	1.2	21	20	N/A	N/A	20	1
6/14/2007	4:30 PM	1.2	19	19	N/A	N/A	19	0
6/14/2007	4:55 PM	1.2	19	19	N/A	N/A	19	0
6/20/2007	8:55 AM	1.2	17	17	N/A	N/A	17	0
6/20/2007	9:15 AM	1.2	20	22	N/A	N/A	21	1
6/20/2007	10:10 AM	1.2	20	20	N/A	N/A	20	0
6/20/2007	10:25 AM	1.2	20	20	N/A	N/A	20	0
6/20/2007	10:45 AM	1.2	21	19	N/A	N/A	20	1
6/20/2007	11:15 AM	1.2	20	21	N/A	N/A	21	0
6/20/2007	11:45 AM	1.2	21	21	N/A	N/A	21	0
6/20/2007	12:15 PM	1.2	22	22	N/A	N/A	22	0
6/20/2007	12:45 PM	1.2	22	23	N/A	N/A	22	1
6/20/2007	1:15 PM	1.2	22	20	N/A	N/A	21	1
6/20/2007	2:15 PM	1.2	19	20	N/A	N/A	20	0
6/20/2007	3:20 PM	1.2	20	21	N/A	N/A	21	0
6/20/2007	3:35 PM	1.2	22	22	N/A	N/A	22	0
6/20/2007	4:00 PM	1.2	23	22	N/A	N/A	22	0
6/20/2007	4:30 PM	1.2	21	21	N/A	N/A	21	0
6/20/2007	4:55 PM	1.2	21	22	N/A	N/A	22	0
7/9/2007	8:55 AM	1.1	17	17	N/A	N/A	17	0
7/9/2007	9:15 AM	1.1	16	16	N/A	N/A	16	0
7/9/2007	10:10 AM	1.1	16	16	N/A	N/A	16	0
7/9/2007	10:25 AM	1.1	16	16	N/A	N/A	16	0
7/9/2007	10:45 AM	1.1	15	16	N/A	N/A	15	0
7/9/2007	11:15 AM	1.1	15	15	N/A	N/A	15	0

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
7/9/2007	11:45 AM	1.1	17	16	N/A	N/A	17	0
7/9/2007	12:15 PM	1.1	16	15	N/A	N/A	15	1
7/9/2007	12:45 PM	1.1	15	14	N/A	N/A	14	0
7/9/2007	1:15 PM	1.1	15	15	N/A	N/A	15	0
7/9/2007	2:15 PM	1.1	15	14	N/A	N/A	15	0
7/9/2007	3:20 PM	1.1	14	15	N/A	N/A	15	0
7/9/2007	3:35 PM	1.1	14	14	N/A	N/A	14	0
7/9/2007	4:00 PM	1.1	15	15	N/A	N/A	15	0
7/9/2007	4:30 PM	1.1	14	14	N/A	N/A	14	0
7/9/2007	4:55 PM	1.1	14	15	N/A	N/A	14	0
7/18/2007	8:55 AM	1.0	14	14	N/A	N/A	14	0
7/18/2007	9:15 AM	1.0	19	19	N/A	N/A	19	0
7/18/2007	10:10 AM	1.0	15	14	N/A	N/A	15	0
7/18/2007	10:25 AM	1.0	14	14	N/A	N/A	14	0
7/18/2007	10:45 AM	1.0	14	14	N/A	N/A	14	0
7/18/2007	11:15 AM	1.0	14	14	N/A	N/A	14	0
7/18/2007	11:45 AM	1.0	14	14	N/A	N/A	14	0
7/18/2007	12:15 PM	1.0	15	14	N/A	N/A	14	0
7/18/2007	12:45 PM	1.0	14	15	N/A	N/A	15	0
7/18/2007	1:15 PM	1.0	15	15	N/A	N/A	15	0
7/18/2007	2:15 PM	1.0	15	15	N/A	N/A	15	0
7/18/2007	3:20 PM	1.0	14	14	N/A	N/A	14	0
7/18/2007	3:35 PM	1.0	15	15	N/A	N/A	15	0
7/18/2007	4:00 PM	1.0	14	14	N/A	N/A	14	0
7/18/2007	4:30 PM	1.0	13	13	N/A	N/A	13	0
7/18/2007	4:55 PM	1.0	14	14	N/A	N/A	14	0
7/28/2007	8:55 AM	0.9	20	20	N/A	N/A	20	0
7/28/2007	9:15 AM	0.9	20	21	N/A	N/A	21	1
7/28/2007	10:10 AM	0.9	21	20	N/A	N/A	21	0
7/28/2007	10:25 AM	0.9	20	21	N/A	N/A	20	0
7/28/2007	10:45 AM	0.9	22	21	N/A	N/A	21	0
7/28/2007	11:15 AM	0.9	20	17	N/A	N/A	18	2
7/28/2007	11:45 AM	0.9	20	21	N/A	N/A	21	0
7/28/2007	12:15 PM	0.9	19	23	N/A	N/A	21	2
7/28/2007	12:45 PM	0.9	24	29	N/A	N/A	26	2
7/28/2007	1:15 PM	0.9	28	27	N/A	N/A	27	1
7/28/2007	2:15 PM	0.9	25	23	N/A	N/A	24	1
7/28/2007	3:20 PM	0.9	23	22	N/A	N/A	22	1
7/28/2007	3:35 PM	0.9	22	21	N/A	N/A	21	0
7/28/2007	4:00 PM	0.9	19	19	N/A	N/A	19	0
7/28/2007	4:30 PM	0.9	20	20	N/A	N/A	20	0
7/28/2007	4:55 PM	0.9	19	20	N/A	N/A	20	0
8/7/2007	8:55 AM	0.8	22	22	N/A	N/A	22	0
8/7/2007	9:15 AM	0.8	19	18	N/A	N/A	18	0
8/7/2007	10:10 AM	0.8	18	17	N/A	N/A	18	0
8/7/2007	10:25 AM	0.8	19	19	N/A	N/A	19	0
8/7/2007	10:45 AM	0.8	19	18	N/A	N/A	19	1

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
8/7/2007	11:15 AM	0.8	18	18	N/A	N/A	18	0
8/7/2007	11:45 AM	0.8	16	16	N/A	N/A	16	0
8/7/2007	12:15 PM	0.8	17	18	N/A	N/A	18	1
8/7/2007	12:45 PM	0.8	17	18	N/A	N/A	18	1
8/7/2007	1:15 PM	0.8	19	18	N/A	N/A	18	0
8/7/2007	2:15 PM	0.8	19	18	N/A	N/A	18	1
8/7/2007	3:20 PM	0.8	17	16	N/A	N/A	16	1
8/7/2007	3:35 PM	0.8	16	16	N/A	N/A	16	0
8/7/2007	4:00 PM	0.8	18	17	N/A	N/A	18	0
8/7/2007	4:30 PM	0.8	18	16	N/A	N/A	17	1
8/7/2007	4:55 PM	0.8	17	16	N/A	N/A	17	0
8/27/2007	8:55 AM	0.7	46	45	N/A	N/A	45	0
8/27/2007	9:15 AM	0.7	48	43	N/A	N/A	46	2
8/27/2007	10:10 AM	0.7	43	42	N/A	N/A	43	0
8/27/2007	10:25 AM	0.7	39	42	N/A	N/A	40	1
8/27/2007	10:45 AM	0.7	46	42	N/A	N/A	44	2
8/27/2007	11:15 AM	0.7	49	46	N/A	N/A	48	1
8/27/2007	11:45 AM	0.7	45	45	N/A	N/A	45	0
8/27/2007	12:15 PM	0.7	44	42	N/A	N/A	43	1
8/27/2007	1:00 PM	0.7	40	43	N/A	N/A	41	2
8/27/2007	1:45 PM	0.7	46	45	N/A	N/A	45	0
8/27/2007	2:30 PM	0.7	45	43	N/A	N/A	44	1
8/27/2007	3:20 PM	0.7	46	41	N/A	N/A	44	3
8/27/2007	3:35 PM	0.7	45	49	N/A	N/A	47	2
8/27/2007	4:00 PM	0.7	49	49	N/A	N/A	49	0
8/27/2007	4:30 PM	0.7	47	44	N/A	N/A	46	1
8/27/2007	4:55 PM	0.7	44	43	N/A	N/A	43	1

[1]Standard deviations were calculated when 3 or 4 replicates were measured. Maximum-average was calculated when 2 replicates were measured.

Table A-16: Cross cycle proprionic acid chemical oxygen demand (COD) concentrations.

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
3/20/2007	8:55 AM	1.7	1.2	1.5	1.3	1.3	1.3	0.1
3/20/2007	9:10 AM	1.7	1.1	1.0	1.0	1.1	1.0	0.0
3/20/2007	9:34 AM	1.7	2.3	2.0	2.0	2.1	2.1	0.1
3/20/2007	10:07 AM	1.7	1.6	1.4	1.3	1.4	1.4	0.1
3/20/2007	10:27 AM	1.7	1.7	1.7	1.8	1.7	1.7	0.1
3/20/2007	12:35 PM	1.7	1.7	1.5	1.5	1.9	1.6	0.2
3/20/2007	2:00 PM	1.7	1.6	1.4	1.5	1.7	1.6	0.1
3/20/2007	3:21 PM	1.7	1.4	1.3	1.3	1.4	1.3	0.1
3/20/2007	3:35 PM	1.7	1.7	1.6	1.6	1.7	1.7	0.1
3/20/2007	5:00 PM	1.7	1.7	1.6	1.7	1.7	1.7	0.0
3/22/2007	8:55 AM	1.7	1.5	1.6	1.5	1.7	1.6	0.1

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
3/22/2007	9:10 AM	1.7	1.8	1.7	1.7	1.6	1.7	0.1
3/22/2007	9:35 AM	1.7	1.3	1.5	1.5	1.3	1.4	0.1
3/22/2007	10:07 AM	1.7	1.3	1.3	1.3	N/A	1.3	0.0
3/22/2007	10:25 AM	1.7	1.4	1.5	1.5	N/A	1.5	0.1
3/22/2007	1:50 PM	1.7	2.0	2.1	2.0	2.1	2.1	0.0
3/22/2007	2:45 PM	1.7	1.4	1.4	1.4	1.4	1.4	0.0
3/22/2007	3:21 PM	1.7	1.8	1.9	1.8	1.8	1.8	0.0
3/22/2007	3:35 PM	1.7	1.2	1.3	1.3	1.4	1.3	0.1
3/22/2007	4:50 PM	1.7	1.9	1.8	1.7	1.6	1.7	0.1
4/20/2007	8:55 AM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	9:10 AM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	9:40 AM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	10:10 AM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	10:25 AM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	10:45 AM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	11:15 AM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	12:30 PM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	2:00 PM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	3:20 PM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	3:35 PM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	4:00 PM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/20/2007	5:00 PM	2.0	0.0	0.0	0.0	0.0	0.0	0.0
4/30/2007	8:55 AM	1.8	0.6	0.0	0.9	1.0	0.6	0.5
4/30/2007	9:10 AM	1.8	1.5	1.4	1.4	1.5	1.5	0.1
4/30/2007	9:25 AM	1.8	0.8	1.1	1.1	1.2	1.0	0.2
4/30/2007	10:10 AM	1.8	1.1	1.2	1.2	1.4	1.2	0.1
4/30/2007	10:25 AM	1.8	1.2	1.3	1.2	1.2	1.2	0.0
4/30/2007	10:40 AM	1.8	1.3	1.3	1.2	1.3	1.3	0.1
4/30/2007	11:00 AM	1.8	1.2	1.6	1.6	1.5	1.4	0.2
4/30/2007	11:30 AM	1.8	1.5	1.2	1.2	1.6	1.4	0.2
4/30/2007	12:00 PM	1.8	1.6	1.6	1.5	1.5	1.6	0.1
4/30/2007	12:40 PM	1.8	1.3	1.4	1.5	1.3	1.4	0.1
4/30/2007	1:30 PM	1.8	1.5	1.4	1.4	1.5	1.5	0.1
4/30/2007	2:00 PM	1.8	1.5	1.3	1.3	1.4	1.4	0.1
4/30/2007	2:45 PM	1.8	1.4	1.3	1.4	1.4	1.4	0.0
4/30/2007	3:20 PM	1.8	0.8	1.1	1.3	1.3	1.1	0.2
4/30/2007	3:35 PM	1.8	1.2	1.3	1.3	1.3	1.3	0.1
4/30/2007	4:00 PM	1.8	1.2	1.0	1.4	1.2	1.2	0.2
4/30/2007	4:30 PM	1.8	1.4	1.4	1.4	1.5	1.4	0.1
4/30/2007	5:00 PM	1.8	1.7	1.5	1.6	1.6	1.6	0.1
5/8/2007	8:55 AM	1.6	0.8	0.9	N/A	N/A	0.8	0.0
5/8/2007	9:10 AM	1.6	0.8	0.8	N/A	N/A	0.8	0.0
5/8/2007	10:10 AM	1.6	0.7	0.7	N/A	N/A	0.7	0.0
5/8/2007	10:25 AM	1.6	0.7	0.7	N/A	N/A	0.7	0.0
5/8/2007	10:40 AM	1.6	0.7	0.8	N/A	N/A	0.7	0.0
5/8/2007	11:00 AM	1.6	0.7	0.7	N/A	N/A	0.7	0.0
5/8/2007	11:30 AM	1.6	0.7	0.6	N/A	N/A	0.7	0.0
5/8/2007	12:00 PM	1.6	0.6	0.5	N/A	N/A	0.5	0.0

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
5/8/2007	12:40 PM	1.6	0.6	0.6	N/A	N/A	0.6	0.0
5/8/2007	1:15 PM	1.6	0.5	0.3	N/A	N/A	0.4	0.2
5/8/2007	2:00 PM	1.6	0.3	0.5	N/A	N/A	0.4	0.1
5/8/2007	2:45 PM	1.6	0.3	0.2	N/A	N/A	0.2	0.0
5/8/2007	3:20 PM	1.6	0.2	0.2	N/A	N/A	0.2	0.0
5/8/2007	3:35 PM	1.6	0.2	0.0	N/A	N/A	0.1	0.1
5/8/2007	4:00 PM	1.6	1.3	0.0	N/A	N/A	0.7	0.9
5/8/2007	5:00 PM	1.6	1.0	0.0	N/A	N/A	0.5	0.7
5/16/2007	8:55 AM	1.5	0.8	0.9	N/A	N/A	0.9	0.0
5/16/2007	9:10 AM	1.5	1.5	1.2	N/A	N/A	1.3	0.2
5/16/2007	10:10 AM	1.5	1.2	1.2	N/A	N/A	1.2	0.0
5/16/2007	10:25 AM	1.5	1.2	1.1	N/A	N/A	1.2	0.1
5/16/2007	10:45 AM	1.5	1.2	1.2	N/A	N/A	1.2	0.0
5/16/2007	11:15 AM	1.5	1.4	1.4	N/A	N/A	1.4	0.0
5/16/2007	11:45 AM	1.5	1.1	1.0	N/A	N/A	1.0	0.0
5/16/2007	12:15 PM	1.5	1.3	1.3	N/A	N/A	1.3	0.0
5/16/2007	1:15 PM	1.5	0.9	0.8	N/A	N/A	0.9	0.1
5/16/2007	2:00 PM	1.5	1.2	1.2	N/A	N/A	1.2	0.0
5/16/2007	2:45 PM	1.5	1.1	1.3	N/A	N/A	1.2	0.1
5/16/2007	3:20 PM	1.5	1.1	1.2	N/A	N/A	1.1	0.0
5/16/2007	4:00 PM	1.5	1.3	1.3	N/A	N/A	1.3	0.0
5/16/2007	4:30 PM	1.5	1.2	1.1	N/A	N/A	1.1	0.1
5/16/2007	5:00 PM	1.5	1.3	1.3	N/A	N/A	1.3	0.0
5/23/2007	8:55 AM	1.4	1.0	1.2	N/A	N/A	1.1	0.1
5/23/2007	9:10 AM	1.4	3.8	3.9	N/A	N/A	3.9	0.1
5/23/2007	9:30 AM	1.4	1.5	1.6	N/A	N/A	1.6	0.1
5/23/2007	10:10 AM	1.4	1.8	1.6	N/A	N/A	1.7	0.1
5/23/2007	10:25 AM	1.4	1.4	1.5	N/A	N/A	1.5	0.1
5/23/2007	10:45 AM	1.4	1.3	1.5	N/A	N/A	1.4	0.1
5/23/2007	11:15 AM	1.4	1.5	1.5	N/A	N/A	1.5	0.0
5/23/2007	11:45 AM	1.4	1.6	1.6	N/A	N/A	1.6	0.0
5/23/2007	12:15 PM	1.4	1.3	1.5	N/A	N/A	1.4	0.2
5/23/2007	1:00 PM	1.4	1.5	1.5	N/A	N/A	1.5	0.0
5/23/2007	2:15 PM	1.4	0.0	0.6	N/A	N/A	0.3	0.4
5/23/2007	3:20 PM	1.4	2.5	3.6	N/A	N/A	3.0	0.8
5/23/2007	3:35 PM	1.4	3.5	4.3	N/A	N/A	3.9	0.5
5/23/2007	3:50 PM	1.4	3.7	3.6	N/A	N/A	3.7	0.1
5/23/2007	4:42 PM	1.4	3.6	2.2	N/A	N/A	2.9	1.0
5/23/2007	4:55 PM	1.4	0.5	0.7	N/A	N/A	0.6	0.1
5/31/2007	8:55 AM	1.3	0.6	0.7	N/A	N/A	0.7	0.1
5/31/2007	9:10 AM	1.3	3.3	3.4	N/A	N/A	3.4	0.1
5/31/2007	9:30 AM	1.3	1.1	1.2	N/A	N/A	1.2	0.1
5/31/2007	10:10 AM	1.3	1.4	1.4	N/A	N/A	1.4	0.0
5/31/2007	10:25 AM	1.3	1.4	1.3	N/A	N/A	1.3	0.1
5/31/2007	10:45 AM	1.3	1.3	1.3	N/A	N/A	1.3	0.0
5/31/2007	11:15 AM	1.3	1.4	1.3	N/A	N/A	1.4	0.1
5/31/2007	11:45 AM	1.3	1.6	1.7	N/A	N/A	1.6	0.0
5/31/2007	12:15 PM	1.3	1.9	1.7	N/A	N/A	1.8	0.2

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
5/31/2007	1:00 PM	1.3	1.8	1.6	N/A	N/A	1.7	0.2
5/31/2007	2:15 PM	1.3	1.8	1.7	N/A	N/A	1.8	0.0
5/31/2007	3:20 PM	1.3	1.8	1.7	N/A	N/A	1.7	0.1
5/31/2007	3:35 PM	1.3	1.5	1.6	N/A	N/A	1.6	0.0
5/31/2007	4:00 PM	1.3	1.7	1.6	N/A	N/A	1.7	0.0
5/31/2007	4:20 PM	1.3	1.8	1.8	N/A	N/A	1.8	0.0
5/31/2007	4:55 PM	1.3	1.5	1.5	N/A	N/A	1.5	0.0
6/14/2007	9:15 AM	1.2	2.1	2.1	N/A	N/A	2.1	0.0
6/14/2007	10:10 AM	1.2	1.0	1.0	N/A	N/A	1.0	0.0
6/14/2007	10:25 AM	1.2	0.8	0.8	N/A	N/A	0.8	0.0
6/14/2007	10:45 AM	1.2	0.8	0.9	N/A	N/A	0.9	0.0
6/14/2007	11:15 AM	1.2	0.9	0.9	N/A	N/A	0.9	0.0
6/14/2007	11:45 AM	1.2	0.8	0.9	N/A	N/A	0.8	0.1
6/14/2007	12:15 PM	1.2	0.8	0.9	N/A	N/A	0.9	0.1
6/14/2007	12:45 PM	1.2	0.8	0.9	N/A	N/A	0.9	0.0
6/14/2007	1:15 PM	1.2	0.9	0.9	N/A	N/A	0.9	0.0
6/14/2007	1:45 PM	1.2	1.1	1.0	N/A	N/A	1.0	0.1
6/14/2007	3:20 PM	1.2	1.1	1.2	N/A	N/A	1.1	0.1
6/14/2007	3:35 PM	1.2	1.3	1.3	N/A	N/A	1.3	0.0
6/14/2007	4:00 PM	1.2	1.1	1.2	N/A	N/A	1.1	0.0
6/14/2007	4:30 PM	1.2	1.2	1.1	N/A	N/A	1.2	0.0
6/14/2007	4:55 PM	1.2	1.0	1.0	N/A	N/A	1.0	0.0
6/20/2007	8:55 AM	1.2	0.8	0.8	N/A	N/A	0.8	0.0
6/20/2007	9:15 AM	1.2	0.9	0.9	N/A	N/A	0.9	0.0
6/20/2007	10:10 AM	1.2	1.0	1.0	N/A	N/A	1.0	0.0
6/20/2007	10:25 AM	1.2	1.0	1.0	N/A	N/A	1.0	0.0
6/20/2007	10:45 AM	1.2	1.0	0.9	N/A	N/A	0.9	0.0
6/20/2007	11:15 AM	1.2	1.1	1.0	N/A	N/A	1.1	0.0
6/20/2007	11:45 AM	1.2	1.0	1.1	N/A	N/A	1.1	0.0
6/20/2007	12:15 PM	1.2	1.0	0.9	N/A	N/A	0.9	0.1
6/20/2007	12:45 PM	1.2	0.9	1.0	N/A	N/A	0.9	0.0
6/20/2007	1:15 PM	1.2	0.9	0.9	N/A	N/A	0.9	0.0
6/20/2007	2:15 PM	1.2	0.8	0.8	N/A	N/A	0.8	0.0
6/20/2007	3:20 PM	1.2	0.7	0.7	N/A	N/A	0.7	0.0
6/20/2007	3:35 PM	1.2	0.7	0.7	N/A	N/A	0.7	0.0
6/20/2007	4:00 PM	1.2	0.7	0.7	N/A	N/A	0.7	0.0
6/20/2007	4:30 PM	1.2	0.7	0.8	N/A	N/A	0.8	0.1
6/20/2007	4:55 PM	1.2	0.8	0.8	N/A	N/A	0.8	0.0
7/9/2007	8:55 AM	1.1	2.8	1.3	N/A	N/A	2.0	1.1
7/9/2007	9:15 AM	1.1	1.2	1.1	N/A	N/A	1.2	0.1
7/9/2007	10:10 AM	1.1	1.2	1.1	N/A	N/A	1.1	0.1
7/9/2007	10:25 AM	1.1	0.8	0.8	N/A	N/A	0.8	0.0
7/9/2007	10:45 AM	1.1	0.8	0.9	N/A	N/A	0.9	0.1
7/9/2007	11:15 AM	1.1	1.0	1.0	N/A	N/A	1.0	0.1
7/9/2007	11:45 AM	1.1	0.8	0.8	N/A	N/A	0.8	0.0
7/9/2007	12:15 PM	1.1	1.0	0.9	N/A	N/A	1.0	0.1
7/9/2007	12:45 PM	1.1	1.0	1.0	N/A	N/A	1.0	0.0
7/9/2007	1:15 PM	1.1	0.7	0.7	N/A	N/A	0.7	0.0

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
7/9/2007	2:15 PM	1.1	0.7	0.6	N/A	N/A	0.6	0.0
7/9/2007	3:20 PM	1.1	0.6	0.7	N/A	N/A	0.7	0.0
7/9/2007	3:35 PM	1.1	0.7	0.6	N/A	N/A	0.7	0.0
7/9/2007	4:00 PM	1.1	0.6	0.7	N/A	N/A	0.6	0.0
7/9/2007	4:30 PM	1.1	0.6	0.6	N/A	N/A	0.6	0.0
7/9/2007	4:55 PM	1.1	0.5	0.5	N/A	N/A	0.5	0.0
7/18/2007	8:55 AM	1.0	0.8	0.8	N/A	N/A	0.8	0.0
7/18/2007	9:15 AM	1.0	0.5	0.5	N/A	N/A	0.5	0.0
7/18/2007	10:10 AM	1.0	0.6	0.6	N/A	N/A	0.6	0.0
7/18/2007	10:25 AM	1.0	0.8	0.8	N/A	N/A	0.8	0.0
7/18/2007	10:45 AM	1.0	0.5	0.5	N/A	N/A	0.5	0.0
7/18/2007	11:15 AM	1.0	0.8	0.7	N/A	N/A	0.7	0.0
7/18/2007	11:45 AM	1.0	0.6	0.7	N/A	N/A	0.7	0.0
7/18/2007	12:15 PM	1.0	0.6	0.6	N/A	N/A	0.6	0.0
7/18/2007	12:45 PM	1.0	0.6	0.6	N/A	N/A	0.6	0.0
7/18/2007	1:15 PM	1.0	0.7	0.7	N/A	N/A	0.7	0.0
7/18/2007	2:15 PM	1.0	0.6	0.6	N/A	N/A	0.6	0.0
7/18/2007	3:20 PM	1.0	0.6	0.6	N/A	N/A	0.6	0.0
7/18/2007	3:35 PM	1.0	0.6	0.6	N/A	N/A	0.6	0.0
7/18/2007	4:00 PM	1.0	0.7	0.7	N/A	N/A	0.7	0.0
7/18/2007	4:30 PM	1.0	1.0	1.0	N/A	N/A	1.0	0.0
7/18/2007	4:55 PM	1.0	0.7	0.6	N/A	N/A	0.7	0.0
7/28/2007	8:55 AM	0.9	1.1	0.7	N/A	N/A	0.9	0.3
7/28/2007	9:15 AM	0.9	0.7	0.7	N/A	N/A	0.7	0.0
7/28/2007	10:10 AM	0.9	0.7	0.7	N/A	N/A	0.7	0.0
7/28/2007	10:25 AM	0.9	0.6	0.6	N/A	N/A	0.6	0.0
7/28/2007	10:45 AM	0.9	0.7	0.7	N/A	N/A	0.7	0.0
7/28/2007	11:15 AM	0.9	0.8	0.7	N/A	N/A	0.7	0.1
7/28/2007	11:45 AM	0.9	0.7	0.7	N/A	N/A	0.7	0.0
7/28/2007	12:15 PM	0.9	0.7	0.6	N/A	N/A	0.7	0.0
7/28/2007	12:45 PM	0.9	1.4	1.2	N/A	N/A	1.3	0.1
7/28/2007	1:15 PM	0.9	1.1	0.9	N/A	N/A	1.0	0.1
7/28/2007	2:15 PM	0.9	0.9	0.9	N/A	N/A	0.9	0.0
7/28/2007	3:20 PM	0.9	0.7	0.7	N/A	N/A	0.7	0.0
7/28/2007	3:35 PM	0.9	0.7	0.8	N/A	N/A	0.8	0.1
7/28/2007	4:00 PM	0.9	0.7	0.7	N/A	N/A	0.7	0.0
7/28/2007	4:30 PM	0.9	0.7	0.8	N/A	N/A	0.7	0.1
7/28/2007	4:55 PM	0.9	0.8	0.8	N/A	N/A	0.8	0.0
8/7/2007	8:55 AM	0.8	1.0	1.0	N/A	N/A	1.0	0.0
8/7/2007	9:15 AM	0.8	1.4	0.8	N/A	N/A	1.1	0.4
8/7/2007	10:10 AM	0.8	0.8	0.7	N/A	N/A	0.7	0.1
8/7/2007	10:25 AM	0.8	0.6	0.6	N/A	N/A	0.6	0.0
8/7/2007	10:45 AM	0.8	0.6	0.6	N/A	N/A	0.6	0.0
8/7/2007	11:15 AM	0.8	0.6	0.6	N/A	N/A	0.6	0.0
8/7/2007	11:45 AM	0.8	0.6	0.5	N/A	N/A	0.5	0.1
8/7/2007	12:15 PM	0.8	0.6	0.5	N/A	N/A	0.5	0.1
8/7/2007	12:45 PM	0.8	0.7	0.6	N/A	N/A	0.7	0.0
8/7/2007	1:15 PM	0.8	0.5	0.6	N/A	N/A	0.6	0.1

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
8/7/2007	2:15 PM	0.8	0.6	0.6	N/A	N/A	0.6	0.0
8/7/2007	3:20 PM	0.8	0.0	0.6	N/A	N/A	0.3	0.4
8/7/2007	3:35 PM	0.8	0.6	0.6	N/A	N/A	0.6	0.0
8/7/2007	4:00 PM	0.8	0.7	0.7	N/A	N/A	0.7	0.0
8/7/2007	4:30 PM	0.8	0.7	0.6	N/A	N/A	0.7	0.0
8/7/2007	4:55 PM	0.8	0.8	0.8	N/A	N/A	0.8	0.0
8/27/2007	8:55 AM	0.7	1.8	1.5	N/A	N/A	1.6	0.2
8/27/2007	9:15 AM	0.7	1.5	1.5	N/A	N/A	1.5	0.0
8/27/2007	10:10 AM	0.7	1.9	1.5	N/A	N/A	1.7	0.3
8/27/2007	10:25 AM	0.7	2.0	2.4	N/A	N/A	2.2	0.3
8/27/2007	10:45 AM	0.7	1.8	1.8	N/A	N/A	1.8	0.1
8/27/2007	11:15 AM	0.7	2.6	1.7	N/A	N/A	2.2	0.7
8/27/2007	11:45 AM	0.7	1.6	1.3	N/A	N/A	1.4	0.2
8/27/2007	12:15 PM	0.7	2.3	2.0	N/A	N/A	2.1	0.2
8/27/2007	1:00 PM	0.7	1.8	2.0	N/A	N/A	1.9	0.1
8/27/2007	1:45 PM	0.7	1.8	1.9	N/A	N/A	1.9	0.0
8/27/2007	2:30 PM	0.7	1.7	2.2	N/A	N/A	1.9	0.3
8/27/2007	3:20 PM	0.7	1.9	1.6	N/A	N/A	1.8	0.2
8/27/2007	3:35 PM	0.7	1.7	2.0	N/A	N/A	1.9	0.2
8/27/2007	4:00 PM	0.7	2.4	2.7	N/A	N/A	2.5	0.2
8/27/2007	4:30 PM	0.7	2.1	2.0	N/A	N/A	2.1	0.1
8/27/2007	4:55 PM	0.7	1.9	1.8	N/A	N/A	1.9	0.1

[1]Standard deviations were calculated when 3 or 4 replicates were measured. Maximum-average was calculated when 2 replicates were measured.

Table A-17: Cross cycle isobutyric acid chemical oxygen demand (COD) concentrations.

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
3/20/2007	8:55 AM	1.7	6.3	7.3	7.6	7.7	7.2	0.6
3/20/2007	9:10 AM	1.7	7.5	7.9	7.6	7.4	7.6	0.2
3/20/2007	9:34 AM	1.7	7.5	7.7	7.4	7.8	7.6	0.2
3/20/2007	10:07 AM	1.7	7.4	7.7	7.7	7.5	7.6	0.1
3/20/2007	10:27 AM	1.7	6.9	7.1	6.9	6.9	6.9	0.1
3/20/2007	12:35 PM	1.7	8.0	7.8	7.1	7.5	7.6	0.4
3/20/2007	2:00 PM	1.7	8.2	7.6	7.6	7.6	7.7	0.3
3/20/2007	3:21 PM	1.7	8.2	7.6	7.7	8.1	7.9	0.3
3/20/2007	3:35 PM	1.7	9.7	9.2	9.3	9.4	9.4	0.2
3/20/2007	5:00 PM	1.7	7.4	7.8	7.6	7.7	7.6	0.2
3/22/2007	8:55 AM	1.7	7.9	8.0	8.0	7.9	7.9	0.1
3/22/2007	9:10 AM	1.7	8.9	8.1	8.1	8.4	8.4	0.4
3/22/2007	9:35 AM	1.7	7.7	7.9	8.1	8.2	8.0	0.2
3/22/2007	10:07 AM	1.7	8.0	7.9	7.9	N/A	7.9	0.1
3/22/2007	10:25 AM	1.7	7.5	7.8	7.9	N/A	7.7	0.2
3/22/2007	1:50 PM	1.7	8.1	7.7	8.1	7.8	7.9	0.2
3/22/2007	2:45 PM	1.7	8.5	8.1	8.6	8.9	8.5	0.3

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
3/22/2007	3:21 PM	1.7	8.2	8.4	8.2	8.4	8.3	0.1
3/22/2007	3:35 PM	1.7	8.3	8.6	9.1	8.9	8.7	0.4
3/22/2007	4:50 PM	1.7	8.2	8.8	8.7	8.8	8.6	0.3
4/20/2007	8:55 AM	2.0	6.2	6.2	5.7	0.0	4.5	3.0
4/20/2007	9:10 AM	2.0	5.4	5.3	4.9	4.8	5.1	0.3
4/20/2007	9:40 AM	2.0	4.6	4.4	4.4	4.6	4.5	0.1
4/20/2007	10:10 AM	2.0	4.4	4.2	4.2	4.1	4.2	0.1
4/20/2007	10:25 AM	2.0	4.0	4.0	4.2	4.0	4.1	0.1
4/20/2007	10:45 AM	2.0	4.1	4.1	4.4	4.2	4.2	0.1
4/20/2007	11:15 AM	2.0	4.5	4.1	4.4	4.2	4.3	0.2
4/20/2007	12:30 PM	2.0	4.2	3.6	3.6	3.6	3.8	0.3
4/20/2007	2:00 PM	2.0	4.5	4.8	4.2	5.0	4.6	0.3
4/20/2007	3:20 PM	2.0	4.0	4.0	4.8	4.6	4.3	0.4
4/20/2007	3:35 PM	2.0	4.4	4.8	4.3	4.3	4.4	0.2
4/20/2007	4:00 PM	2.0	4.5	4.7	4.2	4.2	4.4	0.3
4/20/2007	5:00 PM	2.0	3.9	3.8	3.5	3.6	3.7	0.2
4/30/2007	8:55 AM	1.8	5.1	5.1	4.8	4.6	4.9	0.3
4/30/2007	9:10 AM	1.8	4.9	5.0	5.0	4.6	4.9	0.2
4/30/2007	9:25 AM	1.8	4.6	4.7	4.4	4.9	4.6	0.2
4/30/2007	10:10 AM	1.8	3.8	4.6	4.0	4.2	4.1	0.3
4/30/2007	10:25 AM	1.8	5.1	5.1	5.2	4.4	4.9	0.3
4/30/2007	10:40 AM	1.8	4.1	4.7	4.3	4.3	4.3	0.3
4/30/2007	11:00 AM	1.8	3.9	4.1	4.6	4.1	4.2	0.3
4/30/2007	11:30 AM	1.8	4.9	4.5	4.0	4.1	4.4	0.4
4/30/2007	12:00 PM	1.8	4.1	4.5	4.3	4.4	4.3	0.2
4/30/2007	12:40 PM	1.8	4.3	4.7	4.7	4.2	4.5	0.3
4/30/2007	1:30 PM	1.8	4.9	4.7	4.7	4.9	4.8	0.1
4/30/2007	2:00 PM	1.8	4.4	4.5	4.1	4.3	4.3	0.2
4/30/2007	2:45 PM	1.8	5.0	4.7	4.8	5.3	4.9	0.3
4/30/2007	3:20 PM	1.8	5.4	5.0	5.2	5.3	5.2	0.2
4/30/2007	3:35 PM	1.8	5.1	5.0	5.0	5.0	5.1	0.1
4/30/2007	4:00 PM	1.8	5.5	4.1	4.7	5.1	4.8	0.6
4/30/2007	4:30 PM	1.8	5.1	5.0	5.4	5.2	5.2	0.2
4/30/2007	5:00 PM	1.8	4.8	4.4	4.5	4.5	4.6	0.2
5/8/2007	8:55 AM	1.6	6.1	6.0	N/A	N/A	6.1	0.1
5/8/2007	9:10 AM	1.6	6.3	5.6	N/A	N/A	6.0	0.5
5/8/2007	10:10 AM	1.6	4.7	4.5	N/A	N/A	4.6	0.1
5/8/2007	10:25 AM	1.6	5.0	4.6	N/A	N/A	4.8	0.2
5/8/2007	10:40 AM	1.6	4.1	4.2	N/A	N/A	4.1	0.1
5/8/2007	11:00 AM	1.6	3.8	3.9	N/A	N/A	3.8	0.1
5/8/2007	11:30 AM	1.6	4.0	3.5	N/A	N/A	3.7	0.3
5/8/2007	12:00 PM	1.6	3.4	3.2	N/A	N/A	3.3	0.2
5/8/2007	12:40 PM	1.6	3.0	2.9	N/A	N/A	2.9	0.1
5/8/2007	1:15 PM	1.6	2.7	2.4	N/A	N/A	2.5	0.2
5/8/2007	2:00 PM	1.6	2.1	1.9	N/A	N/A	2.0	0.1
5/8/2007	2:45 PM	1.6	1.8	1.4	N/A	N/A	1.6	0.2
5/8/2007	3:20 PM	1.6	1.2	1.0	N/A	N/A	1.1	0.1
5/8/2007	3:35 PM	1.6	1.0	0.0	N/A	N/A	0.5	0.7

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
5/8/2007	4:00 PM	1.6	0.0	0.0	N/A	N/A	0.0	0.0
5/8/2007	5:00 PM	1.6	0.0	0.0	N/A	N/A	0.0	0.0
5/16/2007	8:55 AM	1.5	6.0	5.4	N/A	N/A	5.7	0.5
5/16/2007	9:10 AM	1.5	7.4	8.1	N/A	N/A	7.8	0.5
5/16/2007	10:10 AM	1.5	6.3	6.1	N/A	N/A	6.2	0.2
5/16/2007	10:25 AM	1.5	6.3	6.0	N/A	N/A	6.2	0.2
5/16/2007	10:45 AM	1.5	6.5	6.3	N/A	N/A	6.4	0.1
5/16/2007	11:15 AM	1.5	6.1	6.0	N/A	N/A	6.0	0.1
5/16/2007	11:45 AM	1.5	6.1	6.3	N/A	N/A	6.2	0.2
5/16/2007	12:15 PM	1.5	6.2	6.2	N/A	N/A	6.2	0.0
5/16/2007	1:15 PM	1.5	6.1	5.7	N/A	N/A	5.9	0.3
5/16/2007	2:00 PM	1.5	5.9	6.1	N/A	N/A	6.0	0.1
5/16/2007	2:45 PM	1.5	5.8	6.0	N/A	N/A	5.9	0.1
5/16/2007	3:20 PM	1.5	6.5	6.4	N/A	N/A	6.4	0.1
5/16/2007	4:00 PM	1.5	6.5	6.3	N/A	N/A	6.4	0.1
5/16/2007	4:30 PM	1.5	6.3	6.4	N/A	N/A	6.3	0.1
5/16/2007	5:00 PM	1.5	5.8	6.1	N/A	N/A	6.0	0.2
5/23/2007	8:55 AM	1.4	6.9	7.5	N/A	N/A	7.2	0.4
5/23/2007	9:10 AM	1.4	10.8	10.4	N/A	N/A	10.6	0.2
5/23/2007	9:30 AM	1.4	9.2	9.5	N/A	N/A	9.4	0.2
5/23/2007	10:10 AM	1.4	9.1	8.9	N/A	N/A	9.0	0.1
5/23/2007	10:25 AM	1.4	8.5	8.3	N/A	N/A	8.4	0.1
5/23/2007	10:45 AM	1.4	7.4	7.6	N/A	N/A	7.5	0.1
5/23/2007	11:15 AM	1.4	7.5	7.6	N/A	N/A	7.6	0.1
5/23/2007	11:45 AM	1.4	8.6	8.4	N/A	N/A	8.5	0.2
5/23/2007	12:15 PM	1.4	8.1	8.3	N/A	N/A	8.2	0.2
5/23/2007	1:00 PM	1.4	8.0	5.8	N/A	N/A	6.9	1.6
5/23/2007	2:15 PM	1.4	0.0	6.7	N/A	N/A	3.4	4.8
5/23/2007	3:20 PM	1.4	7.2	7.0	N/A	N/A	7.1	0.1
5/23/2007	3:35 PM	1.4	7.5	7.1	N/A	N/A	7.3	0.3
5/23/2007	3:50 PM	1.4	6.8	6.7	N/A	N/A	6.8	0.1
5/23/2007	4:42 PM	1.4	6.8	6.8	N/A	N/A	6.8	0.0
5/23/2007	4:55 PM	1.4	7.0	6.7	N/A	N/A	6.9	0.2
5/31/2007	8:55 AM	1.3	6.7	6.7	N/A	N/A	6.7	0.0
5/31/2007	9:10 AM	1.3	8.7	8.7	N/A	N/A	8.7	0.0
5/31/2007	9:30 AM	1.3	7.3	7.8	N/A	N/A	7.5	0.3
5/31/2007	10:10 AM	1.3	6.5	6.0	N/A	N/A	6.3	0.3
5/31/2007	10:25 AM	1.3	5.3	4.7	N/A	N/A	5.0	0.4
5/31/2007	10:45 AM	1.3	5.8	5.6	N/A	N/A	5.7	0.1
5/31/2007	11:15 AM	1.3	5.8	5.6	N/A	N/A	5.7	0.2
5/31/2007	11:45 AM	1.3	5.1	5.1	N/A	N/A	5.1	0.0
5/31/2007	12:15 PM	1.3	5.9	4.9	N/A	N/A	5.4	0.7
5/31/2007	1:00 PM	1.3	6.5	5.3	N/A	N/A	5.9	0.8
5/31/2007	2:15 PM	1.3	5.9	5.7	N/A	N/A	5.8	0.1
5/31/2007	3:20 PM	1.3	6.0	6.1	N/A	N/A	6.1	0.1
5/31/2007	3:35 PM	1.3	5.7	5.8	N/A	N/A	5.7	0.1
5/31/2007	4:00 PM	1.3	5.4	5.5	N/A	N/A	5.5	0.1
5/31/2007	4:20 PM	1.3	4.6	4.5	N/A	N/A	4.5	0.1

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
5/31/2007	4:55 PM	1.3	5.1	5.6	N/A	N/A	5.4	0.4
6/14/2007	9:15 AM	1.2	7.5	7.9	N/A	N/A	7.7	0.3
6/14/2007	10:10 AM	1.2	6.3	6.1	N/A	N/A	6.2	0.1
6/14/2007	10:25 AM	1.2	5.5	5.7	N/A	N/A	5.6	0.1
6/14/2007	10:45 AM	1.2	5.7	5.6	N/A	N/A	5.6	0.1
6/14/2007	11:15 AM	1.2	5.5	5.6	N/A	N/A	5.5	0.1
6/14/2007	11:45 AM	1.2	4.7	5.4	N/A	N/A	5.0	0.5
6/14/2007	12:15 PM	1.2	5.5	5.7	N/A	N/A	5.6	0.2
6/14/2007	12:45 PM	1.2	5.3	5.0	N/A	N/A	5.2	0.2
6/14/2007	1:15 PM	1.2	5.1	5.7	N/A	N/A	5.4	0.4
6/14/2007	1:45 PM	1.2	4.1	3.4	N/A	N/A	3.8	0.5
6/14/2007	3:20 PM	1.2	5.6	5.8	N/A	N/A	5.7	0.1
6/14/2007	3:35 PM	1.2	6.3	5.6	N/A	N/A	5.9	0.5
6/14/2007	4:00 PM	1.2	6.0	5.8	N/A	N/A	5.9	0.1
6/14/2007	4:30 PM	1.2	5.3	5.3	N/A	N/A	5.3	0.0
6/14/2007	4:55 PM	1.2	5.6	5.7	N/A	N/A	5.7	0.0
6/20/2007	8:55 AM	1.2	5.1	5.2	N/A	N/A	5.1	0.1
6/20/2007	9:15 AM	1.2	6.4	6.5	N/A	N/A	6.5	0.1
6/20/2007	10:10 AM	1.2	5.4	5.9	N/A	N/A	5.7	0.4
6/20/2007	10:25 AM	1.2	5.5	5.6	N/A	N/A	5.6	0.1
6/20/2007	10:45 AM	1.2	6.3	5.1	N/A	N/A	5.7	0.8
6/20/2007	11:15 AM	1.2	6.0	5.5	N/A	N/A	5.8	0.4
6/20/2007	11:45 AM	1.2	5.8	6.4	N/A	N/A	6.1	0.4
6/20/2007	12:15 PM	1.2	7.5	7.1	N/A	N/A	7.3	0.3
6/20/2007	12:45 PM	1.2	7.0	7.0	N/A	N/A	7.0	0.0
6/20/2007	1:15 PM	1.2	7.4	6.6	N/A	N/A	7.0	0.5
6/20/2007	2:15 PM	1.2	6.2	6.6	N/A	N/A	6.4	0.3
6/20/2007	3:20 PM	1.2	7.0	6.9	N/A	N/A	6.9	0.1
6/20/2007	3:35 PM	1.2	7.6	6.7	N/A	N/A	7.1	0.6
6/20/2007	4:00 PM	1.2	7.5	7.4	N/A	N/A	7.5	0.0
6/20/2007	4:30 PM	1.2	6.9	6.7	N/A	N/A	6.8	0.1
6/20/2007	4:55 PM	1.2	7.0	7.1	N/A	N/A	7.0	0.1
7/9/2007	8:55 AM	1.1	5.5	5.2	N/A	N/A	5.3	0.2
7/9/2007	9:15 AM	1.1	5.3	4.8	N/A	N/A	5.0	0.4
7/9/2007	10:10 AM	1.1	5.3	5.5	N/A	N/A	5.4	0.2
7/9/2007	10:25 AM	1.1	5.1	4.9	N/A	N/A	5.0	0.1
7/9/2007	10:45 AM	1.1	4.9	5.0	N/A	N/A	4.9	0.1
7/9/2007	11:15 AM	1.1	4.6	4.6	N/A	N/A	4.6	0.0
7/9/2007	11:45 AM	1.1	5.6	5.1	N/A	N/A	5.3	0.4
7/9/2007	12:15 PM	1.1	4.8	4.5	N/A	N/A	4.7	0.2
7/9/2007	12:45 PM	1.1	4.6	4.5	N/A	N/A	4.6	0.1
7/9/2007	1:15 PM	1.1	4.3	4.3	N/A	N/A	4.3	0.0
7/9/2007	2:15 PM	1.1	4.5	4.3	N/A	N/A	4.4	0.1
7/9/2007	3:20 PM	1.1	4.6	4.0	N/A	N/A	4.3	0.4
7/9/2007	3:35 PM	1.1	4.5	4.5	N/A	N/A	4.5	0.0
7/9/2007	4:00 PM	1.1	4.5	4.5	N/A	N/A	4.5	0.0
7/9/2007	4:30 PM	1.1	4.5	4.5	N/A	N/A	4.5	0.0
7/9/2007	4:55 PM	1.1	4.2	4.2	N/A	N/A	4.2	0.0

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
7/18/2007	8:55 AM	1.0	4.0	4.3	N/A	N/A	4.1	0.3
7/18/2007	9:15 AM	1.0	4.9	5.0	N/A	N/A	4.9	0.1
7/18/2007	10:10 AM	1.0	4.3	4.4	N/A	N/A	4.4	0.1
7/18/2007	10:25 AM	1.0	4.2	4.3	N/A	N/A	4.2	0.0
7/18/2007	10:45 AM	1.0	4.1	4.2	N/A	N/A	4.1	0.0
7/18/2007	11:15 AM	1.0	4.3	4.2	N/A	N/A	4.2	0.1
7/18/2007	11:45 AM	1.0	4.1	4.5	N/A	N/A	4.3	0.3
7/18/2007	12:15 PM	1.0	4.1	4.1	N/A	N/A	4.1	0.0
7/18/2007	12:45 PM	1.0	4.3	4.0	N/A	N/A	4.2	0.2
7/18/2007	1:15 PM	1.0	4.0	4.2	N/A	N/A	4.1	0.1
7/18/2007	2:15 PM	1.0	4.3	4.2	N/A	N/A	4.2	0.0
7/18/2007	3:20 PM	1.0	4.3	4.0	N/A	N/A	4.1	0.2
7/18/2007	3:35 PM	1.0	4.0	4.0	N/A	N/A	4.0	0.0
7/18/2007	4:00 PM	1.0	3.8	3.8	N/A	N/A	3.8	0.0
7/18/2007	4:30 PM	1.0	3.7	3.6	N/A	N/A	3.6	0.0
7/18/2007	4:55 PM	1.0	3.9	3.9	N/A	N/A	3.9	0.0
7/28/2007	8:55 AM	0.9	5.7	5.6	N/A	N/A	5.7	0.1
7/28/2007	9:15 AM	0.9	6.3	6.5	N/A	N/A	6.4	0.1
7/28/2007	10:10 AM	0.9	5.9	5.4	N/A	N/A	5.6	0.3
7/28/2007	10:25 AM	0.9	5.4	5.4	N/A	N/A	5.4	0.0
7/28/2007	10:45 AM	0.9	5.8	5.9	N/A	N/A	5.9	0.0
7/28/2007	11:15 AM	0.9	5.4	4.8	N/A	N/A	5.1	0.4
7/28/2007	11:45 AM	0.9	5.5	5.6	N/A	N/A	5.6	0.1
7/28/2007	12:15 PM	0.9	5.5	5.5	N/A	N/A	5.5	0.0
7/28/2007	12:45 PM	0.9	4.4	5.3	N/A	N/A	4.9	0.7
7/28/2007	1:15 PM	0.9	5.3	5.4	N/A	N/A	5.3	0.1
7/28/2007	2:15 PM	0.9	5.2	5.1	N/A	N/A	5.1	0.1
7/28/2007	3:20 PM	0.9	4.8	5.1	N/A	N/A	4.9	0.2
7/28/2007	3:35 PM	0.9	5.1	5.2	N/A	N/A	5.2	0.0
7/28/2007	4:00 PM	0.9	5.1	4.6	N/A	N/A	4.8	0.3
7/28/2007	4:30 PM	0.9	4.9	4.8	N/A	N/A	4.8	0.0
7/28/2007	4:55 PM	0.9	4.9	4.9	N/A	N/A	4.9	0.0
8/7/2007	8:55 AM	0.8	4.8	4.8	N/A	N/A	4.8	0.0
8/7/2007	9:15 AM	0.8	5.5	5.2	N/A	N/A	5.3	0.2
8/7/2007	10:10 AM	0.8	5.2	5.3	N/A	N/A	5.2	0.0
8/7/2007	10:25 AM	0.8	5.4	5.4	N/A	N/A	5.4	0.0
8/7/2007	10:45 AM	0.8	5.6	4.9	N/A	N/A	5.3	0.5
8/7/2007	11:15 AM	0.8	5.2	4.7	N/A	N/A	4.9	0.3
8/7/2007	11:45 AM	0.8	4.6	4.6	N/A	N/A	4.6	0.0
8/7/2007	12:15 PM	0.8	4.8	4.7	N/A	N/A	4.7	0.0
8/7/2007	12:45 PM	0.8	4.6	4.7	N/A	N/A	4.7	0.1
8/7/2007	1:15 PM	0.8	4.8	4.7	N/A	N/A	4.8	0.1
8/7/2007	2:15 PM	0.8	4.6	4.7	N/A	N/A	4.6	0.1
8/7/2007	3:20 PM	0.8	4.5	4.2	N/A	N/A	4.4	0.2
8/7/2007	3:35 PM	0.8	3.9	4.1	N/A	N/A	4.0	0.1
8/7/2007	4:00 PM	0.8	4.5	4.6	N/A	N/A	4.5	0.1
8/7/2007	4:30 PM	0.8	4.4	4.2	N/A	N/A	4.3	0.2
8/7/2007	4:55 PM	0.8	4.3	4.3	N/A	N/A	4.3	0.0

Date	Time	DO mg/L	Rep 1 COD (mg/L)	Rep 2 COD (mg/L)	Rep 3 COD (mg/L)	Rep 4 COD (mg/L)	Average COD (mg/L)	Standard deviation / maximum-min[1] (mg/L COD)
8/27/2007	8:55 AM	0.7	19.7	19.2	N/A	N/A	19.4	0.3
8/27/2007	9:15 AM	0.7	19.8	18.2	N/A	N/A	19.0	1.1
8/27/2007	10:10 AM	0.7	17.9	18.0	N/A	N/A	17.9	0.1
8/27/2007	10:25 AM	0.7	15.4	17.5	N/A	N/A	16.4	1.5
8/27/2007	10:45 AM	0.7	18.0	14.2	N/A	N/A	16.1	2.7
8/27/2007	11:15 AM	0.7	17.7	17.0	N/A	N/A	17.4	0.5
8/27/2007	11:45 AM	0.7	16.7	16.9	N/A	N/A	16.8	0.2
8/27/2007	12:15 PM	0.7	15.9	15.0	N/A	N/A	15.5	0.7
8/27/2007	1:00 PM	0.7	16.6	15.5	N/A	N/A	16.1	0.7
8/27/2007	1:45 PM	0.7	16.4	16.3	N/A	N/A	16.4	0.1
8/27/2007	2:30 PM	0.7	15.6	15.8	N/A	N/A	15.7	0.1
8/27/2007	3:20 PM	0.7	15.3	13.9	N/A	N/A	14.6	1.0
8/27/2007	3:35 PM	0.7	14.9	16.5	N/A	N/A	15.7	1.2
8/27/2007	4:00 PM	0.7	14.1	15.5	N/A	N/A	14.8	1.0
8/27/2007	4:30 PM	0.7	15.0	13.8	N/A	N/A	14.4	0.9
8/27/2007	4:55 PM	0.7	14.4	14.0	N/A	N/A	14.2	0.3

[1]Standard deviations were calculated when 3 or 4 replicates were measured. Maximum-average was calculated when 2 replicates were measured.

Table A-18: Cross cycle VSS concentrations.

Date	DO (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)
4/20/2007	2	11400	9900	9100	10133	1168
4/30/2007	1.8	11000	10400	11100	10833	379
5/8/2007	1.6	7900	6600	8900	7800	1153
5/16/2007	1.5	7700	7600	7700	7667	58
5/23/2007	1.4	7700	7600	7700	7667	58
5/31/2007	1.3	8200	9200	7000	8133	1102
6/20/2007	1.2	8900	8600	9000	8833	208
7/9/2007	1.1	8400	7300	7700	7800	557
7/18/2007	1.0	8600	8100	8500	8400	265
7/28/2007	0.9	12000	10500	11700	11400	794
8/7/2007	0.8	10400	10000	9800	10067	306
8/27/2007	0.7	12720	12420	12660	12600	159
		Average:			8990	
		Standard deviation:			1375	

Table A-19: TAN removal rates and times using TAN values from Table A-11.

Date	DO set point	TAN removal rate	TAN removal rate	Time required for complete TAN removal.
	mg/L	(mg/L N day^{-1})	(mg N day^{-1} g VSS^{-1})	hours
4/20/2007	2	57.7	5.7	2.23
4/30/2007	1.8	58.6	5.4	2.6
5/8/2007	1.6	87.8	11.2	2.2
5/16/2007	1.5	89.9	11.6	3.2
5/23/2007	1.4	73.6	9.6	2.9
5/31/2007	1.3	63.6	7.8	3.2
6/20/2007	1.2	57.4	6.5	2.7
7/9/2007	1.1	86.0	11.0	2.7
7/18/2007	1.0	55.7	6.6	3.0
7/28/2007	0.9	39.6	3.5	4.3
8/7/2007	0.8	30.9	3.1	3.2
8/27/2007	0.7	13.3	1.1	3.8
Average (DO 0.8-2.0)			7.5	2.7
Standard deviation (DO 0.8-2.0)			3	0.6

Table A-20: Maximum ratios of NO_2^-:NO_3^- to determine optimum time of cycled aeration required to achieve N removal via NO_2^- only.

Date	DO set point (mg/L)	Maximum ratio of NO_2^-:NO_3^-	Time of maximum ratio NO_2^-:NO_3^- (hours of aerobic time)	NO_3^- at time of maximum NO_2^-:NO_3^-	% NO_3^- of removed TAN at time of maximum NO_2^-:NO_3^-
5/23/2007	1.4	6.90	1.08	0.33	4%
5/31/2007	1.3	4.62	1.08	0.34	4%
6/20/2007	1.2	5.08	1.08	0.16	2%
7/9/2007	1.1	5.35	1.58	0.30	3%
7/18/2007	1.0	2.99	2.58	0.56	8%
7/28/2007	0.9	3.55	1.58	0.07	1%
8/7/2007	0.8	3.21	1.58	0.13	3%
	Average		1.51		4%
	Standard deviation		0.53		2%

APPENDIX B: Fermenter effluent SCOD and VFA concentration data

B.1 LAB SCALE FERMENTER PERFORMANCE

Table B-1 Theoretical COD equivalents for VFA compounds Grady et al. (1999).

VFA	Formula	COD equivalent
Acetic	CH_3COOH	1.07
Proprionic	$C_3H_6O_2$	1.51
Isobutyric	$C_4H_8O_2$	1.82
Butyric	$C_4H_8O_2$	1.82
Isovaleric	$C_5H_{10}O_2$	2.04
Valeric	$C_5H_{10}O_2$	2.04
Isocaproic	$C_6H_{12}O_2$	2.13
Hexanoic	$C_6H_{12}O_2$	2.13
Heptanoic	$C_7H_{14}O_2$	2.34

Table B-2: Laboratory fermenter effluent acetic acid concentrations using COD equivalent factors from Table B-1.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard deviation (mg/L)	Average COD (mg/L)	Standard deviation (COD-mg/L)
2/23/06	30	1734	1739	1763	1746	16	1868	17
2/27/06	34	1624	1562	1574	1587	33	1698	35
3/2/06	37	2017	1976	1960	1984	29	2123	31
3/7/06	42	2037	2003	1982	2007	28	2148	30
3/10/06	45	1932	1865	1805	1867	63	1998	68
3/14/06	49	2032	2000	2012	2015	16	2156	18
3/22/06	57	1918	1881	1896	1898	19	2031	20
3/28/06	63	1812	1655	1689	1719	83	1839	88
4/1/06	67	2362	2141	2346	2283	123	2443	132
4/6/06	72	1913	1856	1887	1885	29	2017	31
4/9/06	75	2256	2251	2172	2226	47	2382	50
4/12/06	78	1938	2035	2036	2003	56	2143	60
4/17/06	83	1564	1464	1598	1542	70	1650	75
					Average		2038	
					Standard deviation		235	

Table B-3: Laboratory fermenter effluent proprionic acid concentrations using COD equivalent factors from Table B-1.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard deviation (mg/L)	Average COD (mg/L)	Standard deviation (COD-mg/L)
2/23/06	30	554	557	564	559	5	843	8
2/27/06	34	485	465	468	473	11	714	16
3/2/06	37	602	590	595	596	6	899	9
3/7/06	42	647	634	632	638	8	963	12
3/10/06	45	633	609	594	612	19	924	29
3/14/06	49	659	652	653	655	4	989	6
3/22/06	57	590	572	593	585	12	884	18
3/28/06	63	584	561	578	575	12	868	18
4/1/06	67	755	756	774	762	10	1150	16
4/6/06	72	652	634	638	641	9	968	14
4/9/06	75	750	758	771	760	10	1147	15
4/12/06	78	701	690	691	694	6	1048	10
4/17/06	83	515	510	516	514	3	776	4
					Average		936	
					Standard deviation		129	

Table B-4: Laboratory fermenter effluent isobutyric acid concentrations using COD equivalent factors from Table B-1.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard deviation (mg/L)	Average COD (mg/L)	Standard deviation (COD-mg/L)
2/23/06	30	83	83	84	83	1	152	2
2/27/06	34	75	73	71	73	2	133	3
3/2/06	37	93	89	92	91	2	166	4
3/7/06	42	93	90	91	91	1	166	2
3/10/06	45	83	78	76	79	4	144	6
3/14/06	49	90	91	93	92	1	167	2
3/22/06	57	84	83	85	84	1	153	1
3/28/06	63	83	81	82	82	1	149	3
4/1/06	67	109	108	108	108	1	197	1
4/6/06	72	95	95	97	96	1	174	2
4/9/06	75	110	111	115	112	3	204	5
4/12/06	78	95	97	98	96	1	176	2
4/17/06	83	69	64	69	67	3	122	5
					Average		162	
					Standard deviation		23	

Table B-5: Laboratory fermenter effluent butyric acid concentrations using COD equivalent factors from Table B-1.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard deviation (mg/L)	Average COD (mg/L)	Standard deviation (COD-mg/L)
2/23/06	30	269	271	273	271	2	493	4
2/27/06	34	228	219	219	222	5	404	9
3/2/06	37	267	261	265	264	3	481	6
3/7/06	42	308	303	301	304	4	553	7
3/10/06	45	287	276	270	278	9	506	16
3/14/06	49	306	298	301	302	4	549	7
3/22/06	57	216	207	216	213	5	388	9
3/28/06	63	249	237	246	244	6	444	11
4/1/06	67	496	492	511	500	10	910	18
4/6/06	72	286	283	283	284	2	517	3
4/9/06	75	515	519	524	519	5	945	8
4/12/06	78	458	453	447	453	5	824	10
4/17/06	83	201	200	203	201	1	367	2
					Average		568	
					Standard deviation		196	

Table B-6: Laboratory fermenter isovaleric acid concentrations using COD equivalent factors from Table B-1.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard deviation (mg/L)	Average COD (mg/L)	Standard deviation (COD-mg/L)
2/23/06	30	71	71	72	71	1	145	1
2/27/06	34	66	64	64	65	1	132	3
3/2/06	37	81	79	80	80	1	163	2
3/7/06	42	78	77	77	77	1	158	2
3/10/06	45	71	67	68	69	2	140	5
3/14/06	49	65	62	63	63	1	129	3
3/22/06	57	66	63	66	65	2	133	3
3/28/06	63	65	62	65	64	2	130	3
4/1/06	67	75	76	78	76	1	155	2
4/6/06	72	76	74	74	75	1	152	2
4/9/06	75	78	80	78	79	1	161	2
4/12/06	78	68	68	68	68	0	139	0
4/17/06	83	56	55	56	56	1	114	1
					Average		142	
					Standard deviation		15	

Table B-7: Laboratory fermenter valeric acid concentrations using COD equivalent factors from Table B-1.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard deviation (mg/L)	Average COD (mg/L)	Standard deviation (COD-mg/L)
2/23/06	30	74	73	74	74	0	150	1
2/27/06	34	68	65	66	66	2	135	3
3/2/06	37	89	87	89	89	1	181	2
3/7/06	42	90	89	89	89	1	182	2
3/10/06	45	88	85	82	85	3	174	6
3/14/06	49	66	63	63	64	1	131	3
3/22/06	57	66	63	66	65	2	132	3
3/28/06	63	74	70	73	72	2	148	4
4/1/06	67	84	84	87	85	2	173	3
4/6/06	72	97	95	94	95	2	195	3
4/9/06	75	82	83	85	83	1	170	2
4/12/06	78	73	72	72	72	1	147	2
4/17/06	83	56	55	56	55	0	113	1
					Average		156	
					Standard deviation		25	

Table B-8: Laboratory fermenter isocaproic concentrations using COD equivalent factors from Table B-1.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard deviation (mg/L)	Average COD (mg/L)	Standard deviation (COD-mg/L)
2/23/06	30	17	17	17	17	0	36	0
2/27/06	34	15	15	14	15	0	32	1
3/2/06	37	17	18	18	18	0	38	1
3/7/06	42	16	16	16	16	0	34	0
3/10/06	45	15	14	14	14	1	30	1
3/14/06	49	22	21	21	21	1	45	1
3/22/06	57	26	25	26	26	1	55	2
3/28/06	63	35	33	35	34	1	73	2
4/1/06	67	50	49	51	50	1	107	2
4/6/06	72	60	59	58	59	1	125	1
4/9/06	75	45	45	46	45	1	97	1
4/12/06	78	35	33	34	34	1	72	1
4/17/06	83	24	24	24	24	0	51	0
					Average		61	
					Standard deviation		31	

Table B-9: Laboratory fermenter hexanoic acid concentrations using COD equivalent factors from Table B-1 (Zero concentration indicates not detected).

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard deviation (mg/L)	Average COD (mg/L)	Standard deviation (COD-mg/L)
2/23/06	30	25	43	44	37	11	79	23
2/27/06	34	43	41	40	41	1	88	3
3/2/06	37	56	56	56	56	0	119	1
3/7/06	42	60	59	59	59	0	126	1
3/10/06	45	56	55	53	55	2	117	3
3/14/06	49	9	9	9	9	0	19	0
3/22/06	57	8	7	7	7	0	16	0
3/28/06	63	9	9	9	9	0	20	1
4/1/06	67	8	7	9	8	1	17	2
4/6/06	72	15	15	14	15	0	32	1
4/9/06	75	0	0	0	0	0	0	0
4/12/06	78	0	0	0	0	0	0	0
4/17/06	83	0	0	0	0	0	0	0
					Average		49	
					Standard deviation		49	

Table B-10: Laboratory fermenter heptanoic acid concentrations using COD equivalent factors from Table B-1.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard deviation (mg/L)	Average COD (mg/L)	Standard deviation (COD-mg/L)
2/23/06	30	11	10	11	10	0	24	1
2/27/06	34	11	10	9	10	1	23	2
3/2/06	37	14	14	14	14	0	33	1
3/7/06	42	14	14	14	14	0	32	0
3/10/06	45	14	13	13	13	1	31	2
3/14/06	49	8	8	8	8	0	19	0
3/22/06	57	14	13	14	14	1	32	1
3/28/06	63	8	8	7	8	0	18	1
4/1/06	67	9	9	9	9	0	21	0
4/6/06	72	10	10	10	10	0	23	1
4/9/06	75	10	8	9	9	1	21	3
4/12/06	78	9	9	9	9	0	20	0
4/17/06	83	8	8	8	8	0	18	1
					Average		24	
					Standard deviation		6	

Table B-11: Total laboratory VFA concentrations.

VFA	Average (mg/L COD)	Standard deviation (mg/L COD)
Acetic	2038	235
Proprionic	936	129
Isobutyric	162	23
Butyric	568	196
Isovaleric	142	15
Valeric	156	25
Isocaproic	61	31
Hexanoic	49	49
Heptanoic	24	6
Sum:	4136	
Maximum Standard deviation:	235	

Table B-12: Laboratory fermenter effluent TAN concenrtation.

Day	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Average TAN (mg/L-N)
80	690.1	709	699.6

B.2 PILOT SCALE FERMENTER PERFORMANCE

Table B-13: Pilot scale fermenter acetic acid concentration.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/7/2006	8	1963	2012	2009	N/A	1995	28	2134	30
9/10/2006	11	1604	1531	1488	N/A	1541	59	1649	63
9/13/2006	14	2103	1962	2007	N/A	2024	72	2166	77
9/18/2006	19	2253	2272	2310	N/A	2278	29	2438	31
9/21/2006	22	2042	2104	1967	N/A	2038	69	2180	73
9/28/2006	29	1890	1901	1783	N/A	1858	65	1988	70
9/30/2006	31	1424	1480	933	N/A	1279	301	1368	322
10/5/2006	36	1430	1393	1373	N/A	1399	29	1496	31
10/8/2006	39	1009	911	1054	N/A	991	73	1061	78
10/13/2006	44	1142	1093	1213	N/A	1149	61	1230	65
10/24/2006	55	1304	1377	1402	N/A	1361	51	1456	54
11/3/2006	65	1514	1573	1356	N/A	1481	112	1585	120
11/7/2006	69	2071	1990	2017	N/A	2026	41	2168	44
11/10/2006	72	1900	1859	1828	N/A	1863	36	1993	39
11/14/2006	76	1518	1536	1506	N/A	1520	15	1627	16
11/20/2006	82	1346	1321	1265	N/A	1311	42	1403	45
12/5/2006	97	1546	1509	1446	N/A	1500	50	1605	54
12/16/2006	108	1913	1919	2088	N/A	1974	100	2112	107
12/27/2006	119	1355	1406	1335	N/A	1365	36	1461	39
1/8/2007	131	1396	1405	1486	N/A	1429	50	1529	53
1/16/07	139	1537	1598	1576	N/A	1570	31	1680	33
1/22/07	145	1310	1329	1302	N/A	1314	14	1406	15
2/2/07	156	1579	1565	1670	N/A	1605	57	1717	61
2/9/07	163	1311	1247	1275	N/A	1278	32	1367	34
2/19/07	173	1109	1072	1049	N/A	1077	30	1152	32
2/23/2007	177	1526	1510	1571	1578	1546	33	1654	35
3/1/2007	183	N/A	N/A	1520	1491	1506	20	1611	22
3/2/2007	184	1533	1469	1515	1489	1501	28	1606	30
3/7/2007	189	1256	1255	1249	1242	1251	7	1338	7
3/9/2007	191	1301	1266	1297	1267	1283	19	1373	20
3/12/2007	194	1405	1443	1475	1451	1443	29	1544	31
3/16/2007	198	1233	1274	1410	1504	1355	125	1450	133
3/19/2007	201	1242	1280	1245	1246	1253	18	1341	19
3/23/2007	205	1258	1297	1300	1296	1288	20	1378	21
3/26/2007	208	1375	1354	1399	1378	1377	18	1473	20
3/30/2007	212	1258	1263	1333	1311	1291	36	1382	39
4/4/2007	217	1244	1213	1268	1277	1250	29	1338	31
4/9/2007	222	1239	1183	1275	1258	1239	40	1326	43
4/24/2007	237	1209	1225	1214	1249	1224	18	1310	19
4/27/2007	240	1279	1276	1289	1328	1293	24	1384	26
5/3/2007	246	1437	1431	1417	1405	1423	14	1522	15
5/14/2007	257	1304	1724	N/A	N/A	1514	297	1620	317
5/21/2007	264	1868	1392	N/A	N/A	1630	336	1744	360
5/29/2007	272	1135	1101	N/A	N/A	1118	24	1197	26
6/6/2007	280	844	847	N/A	N/A	846	3	905	3
6/12/2007	286	571	552	N/A	N/A	561	14	601	15

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
6/23/2007	297	622	662	N/A	N/A	642	28	687	30
7/6/2007	310	1352	1312	1256	1253	1293	48	1384	51
7/24/2007	328	883	889	925	926	906	23	969	24
8/28/2007	363	2099	2133	2116	2206	2138	47	2288	50
					Average (days 0-363):			1528	
					Standard deviation (days 0-363):			383	
					Average (days 98-363):			1420	
					Standard deviation (days 98-363):			333	

Table B-14: Pilot scale fermenter effluent proprionic acid concentrations.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/7/2006	8	639	670	656	N/A	655	15	989	23
9/10/2006	11	565	544	504	N/A	538	31	812	47
9/13/2006	14	813	781	778	N/A	791	20	1194	30
9/18/2006	19	964	963	985	N/A	971	13	1466	19
9/21/2006	22	860	871	800	N/A	844	39	1274	58
9/28/2006	29	678	703	659	N/A	680	22	1027	33
9/30/2006	31	88	88	48	N/A	75	23	113	35
10/5/2006	36	514	495	501	N/A	504	10	761	15
10/8/2006	39	358	298	363	N/A	340	36	513	54
10/13/2006	44	390	362	425	N/A	392	31	592	47
10/24/2006	55	453	481	506	N/A	480	26	725	39
11/3/2006	65	627	661	562	N/A	617	50	931	76
11/7/2006	69	902	872	898	N/A	891	16	1345	24
11/10/2006	72	861	849	826	N/A	845	18	1277	27
11/14/2006	76	625	600	615	N/A	614	13	927	19
11/20/2006	82	566	561	533	N/A	553	18	835	27
12/5/2006	97	577	510	484	N/A	524	48	791	73
12/16/2006	108	802	776	837	N/A	805	31	1216	46
12/27/2006	119	615	633	623	N/A	624	9	942	14
1/8/2007	131	638	650	650	N/A	646	7	975	10
1/16/07	139	625	657	642	N/A	641	16	968	24
1/22/07	145	470	487	483	N/A	480	9	725	14
2/2/07	156	625	580	632	N/A	612	28	924	42
2/9/07	163	511	474	469	N/A	485	23	732	34
2/19/07	173	361	343	342	N/A	349	11	526	17
2/23/2007	177	576	565	580	590	578	10	872	16
3/1/2007	183	672	663	669	666	667	4	1008	6
3/2/2007	184	684	661	670	669	671	10	1013	15
3/7/2007	189	453	445	449	449	449	3	678	5
3/9/2007	191	508	491	502	495	499	7	753	11
3/12/2007	194	561	585	597	589	583	15	880	23
3/16/2007	198	539	567	614	647	592	48	893	73
3/19/2007	201	428	437	433	442	435	6	657	9
3/23/2007	205	465	475	485	485	477	9	721	14
3/26/2007	208	592	595	610	604	600	8	907	13

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
3/30/2007	212	495	500	530	521	511	17	772	25
4/4/2007	217	496	489	510	511	501	10	757	16
4/9/2007	222	424	406	436	429	424	13	640	20
4/24/2007	237	471	470	473	485	475	7	717	11
4/27/2007	240	452	450	452	469	456	9	688	13
5/3/2007	246	479	478	475	465	474	6	716	10
5/14/2007	257	441	588	N/A	N/A	514	104	777	158
5/21/2007	264	724	543	N/A	N/A	633	128	956	193
5/29/2007	272	342	344	N/A	N/A	343	1	517	2
6/6/2007	280	190	188	N/A	N/A	189	2	286	2
6/12/2007	286	206	201	N/A	N/A	204	3	307	5
6/23/2007	297	187	198	N/A	N/A	193	8	291	12
7/6/2007	310	446	437	417	419	430	14	649	21
7/24/2007	328	229	231	239	242	235	6	355	10
8/28/2007	363	895	897	863	921	894	23	1350	35
					Average (days 0-363):			815	
					Standard deviation (days 0-363):			287	
					Average (days 98-363):			763	
					Standard deviation (days 98-363):			245	

Table B-15: Pilot scale fermenter effluent isobutyric acid concentrations.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/7/2006	8	89	93	90	N/A	91	2	166	4
9/10/2006	11	76	75	73	N/A	75	1	136	2
9/13/2006	14	83	83	83	N/A	83	0	151	1
9/18/2006	19	84	84	83	N/A	84	1	152	1
9/21/2006	22	83	83	82	N/A	83	0	151	1
9/28/2006	29	63	63	61	N/A	62	1	113	3
9/30/2006	31	75	78	45	N/A	66	18	120	33
10/5/2006	36	66	68	65	N/A	66	1	120	3
10/8/2006	39	64	61	61	N/A	62	2	113	3
10/13/2006	44	67	67	72	N/A	68	3	125	5
10/24/2006	55	67	68	69	N/A	68	1	124	2
11/3/2006	65	81	78	79	N/A	79	2	144	4
11/7/2006	69	87	89	88	N/A	88	1	161	2
11/10/2006	72	83	83	83	N/A	83	0	151	0
11/14/2006	76	73	68	71	N/A	70	3	128	5
11/20/2006	82	76	73	74	N/A	74	1	135	2
12/5/2006	97	105	72	69	N/A	82	20	149	37
12/16/2006	108	73	71	78	N/A	74	3	135	6
12/27/2006	119	61	61	43	N/A	55	10	100	19
1/8/2007	131	42	57	48	N/A	49	8	89	14
1/16/07	139	59	53	54	N/A	55	3	101	5
1/22/07	145	50	52	56	N/A	52	3	95	5
2/2/07	156	57	39	60	N/A	52	11	95	20
2/9/07	163	54	53	51	N/A	52	1	96	2
2/19/07	173	45	44	44	N/A	44	1	81	2

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
2/23/2007	177	49	47	49	49	48	1	88	2
3/1/2007	183	N/A	N/A	48	50	49	1	89	2
3/2/2007	184	0	0	0	0	0	0	0	0
3/7/2007	189	46	39	46	45	44	4	80	7
3/9/2007	191	48	48	47	46	47	1	86	2
3/12/2007	194	50	52	53	51	52	1	94	2
3/16/2007	198	50	51	51	51	51	1	92	1
3/19/2007	201	45	46	47	47	46	1	84	2
3/23/2007	205	45	47	45	47	46	1	84	2
3/26/2007	208	57	52	54	52	54	2	98	4
3/30/2007	212	48	48	52	51	50	2	91	4
4/4/2007	217	47	46	49	49	48	2	87	3
4/9/2007	222	48	46	47	47	47	1	86	1
4/24/2007	237	42	50	47	49	47	4	85	6
4/27/2007	240	41	40	41	41	41	0	75	1
5/3/2007	246	40	41	40	39	40	1	73	1
5/14/2007	257	40	45	N/A	N/A	42	4	77	7
5/21/2007	264	61	48	N/A	N/A	55	9	99	17
5/29/2007	272	26	30	N/A	N/A	28	3	51	5
6/6/2007	280	42	39	N/A	N/A	40	2	74	4
6/12/2007	286	42	47	N/A	N/A	44	3	80	6
6/23/2007	297	26	22	N/A	N/A	24	3	44	5
7/6/2007	310	47	41	47	43	44	3	81	5
7/24/2007	328	15	28	25	22	22	6	40	10
8/28/2007	363	83	79	91	93	86	6	157	12
					Average (days 0-363):			103	
					Standard deviation (days 0-363):			34	
					Average (days 98-363):			84	
					Standard deviation (days 98-363):			26	

Table B-16: Pilot scale fermenter effluent butyric acid concentrations.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/7/2006	8	276	274	270	N/A	273	3	497	5
9/10/2006	11	190	182	164	N/A	178	13	325	24
9/13/2006	14	270	254	251	N/A	258	10	470	18
9/18/2006	19	268	261	288	N/A	272	14	495	25
9/21/2006	22	253	259	232	N/A	248	14	451	25
9/28/2006	29	274	267	237	N/A	260	20	472	36
9/30/2006	31	28	29	16	N/A	25	7	45	13
10/5/2006	36	142	138	138	N/A	139	2	254	4
10/8/2006	39	82	71	83	N/A	79	7	143	12
10/13/2006	44	85	78	89	N/A	84	5	153	9
10/24/2006	55	96	102	103	N/A	100	4	182	7
11/3/2006	65	210	220	184	N/A	205	18	372	33
11/7/2006	69	302	281	296	N/A	293	11	533	20
11/10/2006	72	271	275	271	N/A	272	2	495	4
11/14/2006	76	221	220	215	N/A	219	3	399	6

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
11/20/2006	82	202	201	189	N/A	197	7	359	13
12/5/2006	97	351	254	197	N/A	267	78	486	141
12/16/2006	108	261	222	276	N/A	253	28	461	51
12/27/2006	119	189	272	191	N/A	218	47	396	86
1/8/2007	131	173	175	189	N/A	179	9	326	17
1/16/07	139	177	225	195	N/A	199	25	362	45
1/22/07	145	133	150	168	N/A	150	18	273	32
2/2/07	156	157	127	163	N/A	149	20	271	36
2/9/07	163	102	109	93	N/A	102	8	185	15
2/19/07	173	58	56	50	N/A	55	5	100	8
2/23/2007	177	34	32	32	33	33	1	60	2
3/1/2007	183	N/A	N/A	58	56	57	1	104	3
3/2/2007	184	70	65	66	65	66	2	121	4
3/7/2007	189	60	58	58	59	59	1	107	1
3/9/2007	191	83	80	82	81	81	1	148	3
3/12/2007	194	95	100	102	102	100	3	182	5
3/16/2007	198	156	113	118	112	125	21	227	38
3/19/2007	201	74	76	75	76	75	1	137	1
3/23/2007	205	94	97	99	98	97	2	177	3
3/26/2007	208	120	121	124	123	122	2	222	3
3/30/2007	212	116	115	122	121	118	4	216	7
4/4/2007	217	93	92	96	96	94	2	172	4
4/9/2007	222	72	69	74	73	72	2	131	4
4/24/2007	237	90	90	90	92	91	1	165	2
4/27/2007	240	66	67	67	69	68	1	123	2
5/3/2007	246	76	75	75	74	75	1	137	1
5/14/2007	257	78	104	N/A	N/A	91	18	166	33
5/21/2007	264	156	118	N/A	N/A	137	26	249	48
5/29/2007	272	80	82	N/A	N/A	81	2	147	3
6/6/2007	280	57	57	N/A	N/A	57	0	104	0
6/12/2007	286	118	116	N/A	N/A	117	2	213	3
6/23/2007	297	36	36	N/A	N/A	36	0	66	0
7/6/2007	310	147	142	136	137	141	5	256	10
7/24/2007	328	102	101	106	104	103	2	188	4
8/28/2007	363	300	299	286	306	298	9	542	16
					Average (days 0-363):			257	
					Standard deviation (days 0-363):			146	
					Average (days 98-363):			204	
					Standard deviation (days 98-363):			111	

Table B-17: Pilot scale fermenter effluent isovaleric acid concentrations.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/7/2006	8	78	77	76	N/A	77	1	157	2
9/10/2006	11	65	59	53	N/A	59	6	120	12
9/13/2006	14	73	69	67	N/A	70	3	142	6
9/18/2006	19	83	80	86	N/A	83	3	169	7
9/21/2006	22	78	79	71	N/A	76	4	155	9

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/28/2006	29	65	67	58	N/A	63	5	129	10
9/30/2006	31	49	53	26	N/A	43	15	87	30
10/5/2006	36	53	53	53	N/A	53	0	109	0
10/8/2006	39	33	29	34	N/A	32	3	65	5
10/13/2006	44	38	32	41	N/A	37	4	76	9
10/24/2006	55	47	50	52	N/A	50	2	102	5
11/3/2006	65	67	70	58	N/A	65	6	132	12
11/7/2006	69	89	86	90	N/A	88	2	180	3
11/10/2006	72	80	81	80	N/A	80	0	164	1
11/14/2006	76	58	57	56	N/A	57	1	116	2
11/20/2006	82	63	63	58	N/A	61	3	125	5
12/5/2006	97	0	0	0	0	0	0	0	0
12/16/2006	108	0	0	0	0	0	0	0	0
12/27/2006	119	0	0	0	0	0	0	0	0
1/8/2007	131	0	0	0	0	0	0	0	0
1/16/07	139	0	0	0	0	0	0	0	0
1/22/07	145	0	0	0	0	0	0	0	0
2/2/07	156	0	0	0	0	0	0	0	0
2/9/07	163	0	0	0	0	0	0	0	0
2/19/07	173	0	0	0	0	0	0	0	0
2/23/2007	177	40	38	40	40	39	1	80	2
3/1/2007	183	N/A	N/A	49	47	48	1	99	3
3/2/2007	184	51	48	49	49	49	1	100	2
3/7/2007	189	40	39	39	40	39	0	80	1
3/9/2007	191	48	46	48	48	47	1	97	1
3/12/2007	194	48	50	49	49	49	1	100	2
3/16/2007	198	54	51	52	53	53	2	107	3
3/19/2007	201	43	45	44	45	44	1	90	2
3/23/2007	205	45	47	47	48	47	1	95	3
3/26/2007	208	56	55	58	56	56	1	115	2
3/30/2007	212	50	50	53	53	52	2	105	3
4/4/2007	217	49	47	50	49	49	1	100	2
4/9/2007	222	49	46	50	49	48	2	99	4
4/24/2007	237	47	47	48	49	48	1	97	1
4/27/2007	240	42	41	42	43	42	1	86	1
5/3/2007	246	41	41	40	41	41	0	83	1
5/14/2007	257	40	52	N/A	N/A	46	9	94	18
5/21/2007	264	68	52	N/A	N/A	60	11	123	22
5/29/2007	272	38	42	N/A	N/A	40	3	81	6
6/6/2007	280	38	40	N/A	N/A	39	1	80	2
6/12/2007	286	39	37	N/A	N/A	38	2	78	3
6/23/2007	297	29	30	N/A	N/A	30	0	61	1
7/6/2007	310	52	56	50	53	53	3	108	6
7/24/2007	328	10	10	11	11	11	0	22	1
8/28/2007	363	73	73	71	72	72	1	148	2
					Average (days 0-363):			87	
					Standard deviation (days 0-363):			50	
					Average (days 98-363):			70	
					Standard deviation (days 98-363):			45	

Table B-18: Pilot scale fermenter effluent valeric acid concentrations.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/7/2006	8	37	36	35	N/A	36	1	74	3
9/10/2006	11	30	26	23	N/A	26	3	53	7
9/13/2006	14	30	30	29	N/A	29	1	60	1
9/18/2006	19	40	37	39	N/A	39	1	79	3
9/21/2006	22	38	40	35	N/A	37	2	76	5
9/28/2006	29	38	39	33	N/A	37	3	75	6
9/30/2006	31	9	9	5	N/A	8	2	16	5
10/5/2006	36	33	32	32	N/A	32	0	66	0
10/8/2006	39	24	20	25	N/A	23	3	47	6
10/13/2006	44	33	31	36	N/A	33	3	68	6
10/24/2006	55	39	42	45	N/A	42	3	85	6
11/3/2006	65	46	48	41	N/A	45	4	92	8
11/7/2006	69	79	74	78	N/A	77	3	158	6
11/10/2006	72	74	71	74	N/A	73	2	149	3
11/14/2006	76	65	64	63	N/A	64	1	131	3
11/20/2006	82	78	78	73	N/A	77	3	156	6
12/5/2006	97	254	161	121	N/A	179	69	364	140
12/16/2006	108	157	139	152	N/A	149	9	305	19
12/27/2006	119	107	110	104	N/A	107	3	218	7
1/8/2007	131	91	93	94	N/A	93	1	189	2
1/16/07	139	74	91	90	N/A	85	10	173	20
1/22/07	145	60	60	61	N/A	60	1	123	1
2/2/07	156	60	59	60	N/A	59	1	121	1
2/9/07	163	39	36	37	N/A	37	2	76	3
2/19/07	173	18	19	16	N/A	18	2	36	3
2/23/2007	177	23	20	21	20	21	1	43	2
3/1/2007	183	N/A	N/A	24	23	24	0	48	1
3/2/2007	184	24	23	24	23	24	0	48	1
3/7/2007	189	21	20	20	20	20	0	41	1
3/9/2007	191	22	21	22	21	21	0	44	1
3/12/2007	194	22	23	24	23	23	1	47	1
3/16/2007	198	45	100	25	N/A	57	39	116	79
3/19/2007	201	21	19	20	19	20	1	40	2
3/23/2007	205	18	18	17	18	18	0	37	1
3/26/2007	208	21	21	21	22	21	0	44	1
3/30/2007	212	20	21	22	20	21	1	42	1
4/4/2007	217	20	19	20	20	20	0	40	1
4/9/2007	222	17	16	18	18	17	1	35	1
4/24/2007	237	18	19	19	19	19	1	39	1
4/27/2007	240	15	15	15	16	15	1	32	1
5/3/2007	246	18	13	14	14	15	2	30	4
5/14/2007	257	11	15	N/A	N/A	13	3	26	5
5/21/2007	264	23	17	N/A	N/A	20	4	40	9
5/29/2007	272	12	12	N/A	N/A	12	1	24	1
6/6/2007	280	11	11	N/A	N/A	11	0	22	0
6/12/2007	286	12	12	N/A	N/A	12	0	25	1
6/23/2007	297	7	8	N/A	N/A	7	0	15	1

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
7/6/2007	310	26	25	24	24	25	1	50	3
7/24/2007	328	10	10	11	11	10	1	21	1
8/28/2007	363	65	65	61	66	64	2	131	5
					Average (days 0-363):			81	
					Standard deviation (days 0-363):			72	
					Average (days 98-363):			70	
					Standard deviation (days 98-363):			67	

Table B-19: Pilot scale fermenter effluent isocaproic acid concentrations (Zero concentration indicates not detected).

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/7/2006	8	14	13	14	N/A	14	1	30	2
9/10/2006	11	14	11	10	N/A	12	2	25	4
9/13/2006	14	12	12	11	N/A	11	0	24	1
9/18/2006	19	17	16	18	N/A	17	1	37	2
9/21/2006	22	20	21	18	N/A	20	2	42	4
9/28/2006	29	17	18	15	N/A	17	1	36	3
9/30/2006	31	12	13	7	N/A	11	3	23	7
10/5/2006	36	10	10	10	N/A	10	0	21	0
10/8/2006	39	5	4	5	N/A	5	1	10	1
10/13/2006	44	5	4	6	N/A	5	1	11	1
10/24/2006	55	9	10	11	N/A	10	1	22	2
11/3/2006	65	8	8	7	N/A	7	1	16	1
11/7/2006	69	19	18	19	N/A	19	1	40	1
11/10/2006	72	15	16	15	N/A	15	0	33	1
11/14/2006	76	13	11	12	N/A	12	1	26	2
11/20/2006	82	9	9	8	N/A	9	1	18	2
12/5/2006	97	0	0	0	0	0	0	0	0
12/16/2006	108	0	0	0	0	0	0	0	0
12/27/2006	119	0	0	0	0	0	0	0	0
1/8/2007	131	0	0	0	0	0	0	0	0
1/16/07	139	0	0	0	0	0	0	0	0
1/22/07	145	0	0	0	0	0	0	0	0
2/2/07	156	0	0	0	0	0	0	0	0
2/9/07	163	0	0	0	0	0	0	0	0
2/19/07	173	0	0	0	0	0	0	0	0
2/23/2007	177	17	15	11	9	13	4	27	8
3/1/2007	183	17	13	7	6	11	5	23	11
3/2/2007	184	3	3	3	3	3	0	7	0
3/7/2007	189	8	8	8	8	8	0	17	0
3/9/2007	191	7	6	7	8	7	1	15	2
3/12/2007	194	7	6	7	6	7	0	14	1
3/16/2007	198	N/A	6	5	3	5	2	10	4
3/19/2007	201	6	7	8	7	7	1	15	2
3/23/2007	205	8	8	9	8	8	1	18	1
3/26/2007	208	9	10	9	10	10	1	21	1
3/30/2007	212	8	9	8	9	8	1	18	1

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
4/4/2007	217	8	7	8	8	8	1	17	1
4/9/2007	222	7	6	8	7	7	1	14	2
4/24/2007	237	9	N/A	9	9	9	0	20	0
4/27/2007	240	8	7	8	7	8	0	16	1
5/3/2007	246	7	7	7	7	7	0	15	1
5/14/2007	257	0	0	0	0	0	0	0	0
5/21/2007	264	0	0	0	0	0	0	0	0
5/29/2007	272	0	0	0	0	0	0	0	0
6/6/2007	280	11	10	N/A	N/A	11	1	22	2
6/12/2007	286	11	12	N/A	N/A	12	1	25	2
6/23/2007	297	6	7	N/A	N/A	6	1	13	2
7/6/2007	310	8	7	6	6	7	1	15	2
7/24/2007	328	5	4	4	4	4	1	9	2
8/28/2007	363	6	5	5	6	6	0	12	1
					Average (days 0-363):			15	
					Standard deviation (days 0-363):			12	
					Average (days 98-363):			11	
					Standard deviation (days 98-363):			9	

Table B-20: Pilot scale fermenter effluent hexanoic acid concentrations (Zero concentration indicates not detected).

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/7/2006	8	4	2	2	N/A	3	1	6	2
9/10/2006	11	8	3	3	N/A	5	3	10	6
9/13/2006	14	0	0	0	N/A	0	0	0	0
9/18/2006	19	1	1	2	N/A	2	0	3	0
9/21/2006	22	1	1	1	N/A	1	0	3	0
9/28/2006	29	1	2	1	N/A	1	0	3	0
9/30/2006	31	1	1	1	N/A	1	0	1	0
10/5/2006	36	7	7	6	N/A	6	0	14	1
10/8/2006	39	0	0	0	N/A	0	0	1	0
10/13/2006	44	0	0	0	N/A	0	0	1	0
10/24/2006	55	0	0	0	N/A	0	0	0	0
11/3/2006	65	9	10	9	N/A	9	1	20	1
11/7/2006	69	0	0	0	0	0	0	0	0
11/10/2006	72	0	0	0	0	0	0	0	0
11/14/2006	76	0	0	0	0	0	0	0	0
11/20/2006	82	0	0	0	0	0	0	0	0
12/5/2006	97	0	0	0	0	0	0	0	0
12/16/2006	108	0	0	0	0	0	0	0	0
12/27/2006	119	0	0	0	0	0	0	0	0
1/8/2007	131	0	0	0	0	0	0	0	0
1/16/07	139	0	0	0	0	0	0	0	0
1/22/07	145	0	0	0	0	0	0	0	0
2/2/07	156	0	0	0	0	0	0	0	0
2/9/07	163	0	0	0	0	0	0	0	0
2/19/07	173	0	0	0	0	0	0	0	0

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
2/23/2007	177	0	0	0	0	0	0	0	0
3/1/2007	183	0	0	0	0	0	0	0	0
3/2/2007	184	0	0	0	0	0	0	0	0
3/7/2007	189	0	0	0	0	0	0	0	0
3/9/2007	191	0	0	0	0	0	0	0	0
3/12/2007	194	0	0	0	0	0	0	0	0
3/16/2007	198	0	0	0	0	0	0	0	0
3/19/2007	201	0	0	0	0	0	0	0	0
3/23/2007	205	0	0	0	0	0	0	0	0
3/26/2007	208	0	0	0	0	0	0	0	0
3/30/2007	212	0	0	0	0	0	0	0	0
4/4/2007	217	0	0	0	0	0	0	0	0
4/9/2007	222	0	0	0	0	0	0	0	0
4/24/2007	237	0	0	0	0	0	0	0	0
4/27/2007	240	0	0	0	0	0	0	0	0
5/3/2007	246	0	0	0	0	0	0	0	0
5/14/2007	257	0	0	0	0	0	0	0	0
5/21/2007	264	0	0	0	0	0	0	0	0
5/29/2007	272	0	0	0	0	0	0	0	0
6/6/2007	280	0	0	0	0	0	0	0	0
6/12/2007	286	0	0	0	0	0	0	0	0
6/23/2007	297	0	0	0	0	0	0	0	0
7/6/2007	310	6	4	5	4	5	1	10	2
7/24/2007	328	3	3	3	3	3	0	6	1
8/28/2007	363	28	30	29	31	29	1	63	3
					Average (days 0-363):			3	
					Standard deviation (days 0-363):			9	
					Average (days 98-363):			2	
					Standard deviation (days 98-363):			11	

Table B-21: Pilot scale fermenter effluent heptanoic acid concentrations (Zero concentration indicates not detected).

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
9/7/2006	8	4	3	3	N/A	3	1	7	1
9/10/2006	11	15	4	4	N/A	8	6	19	14
9/13/2006	14	0	0	0	N/A	0	0	0	0
9/18/2006	19	0	0	0	N/A	0	0	0	0
9/21/2006	22	0	0	0	N/A	0	0	0	0
9/28/2006	29	0	0	0	N/A	0	0	0	0
9/30/2006	31	0	0	0	N/A	0	0	0	0
10/5/2006	36	29	31	30	N/A	30	1	70	3
10/8/2006	39	0	0	0	N/A	0	0	0	0
10/13/2006	44	3	3	3	N/A	3	0	8	1
10/24/2006	55	5	6	5	N/A	5	1	13	1
11/3/2006	65	12	11	11	N/A	11	1	26	1
11/7/2006	69	28	31	31	N/A	30	1	70	3
11/10/2006	72	5	6	6	N/A	6	1	14	1

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Rep 4 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)	Average COD (mg/L)	Standard Deviation COD (mg/L)
11/14/2006	76	35	34	34	N/A	34	0	80	1
11/20/2006	82	14	14	12	N/A	13	1	31	2
12/5/2006	97	301	137	100	N/A	180	107	421	250
12/16/2006	108	80	65	63	N/A	69	9	162	21
12/27/2006	119	46	42	38	N/A	42	4	98	9
1/8/2007	131	34	31	32	N/A	33	1	77	3
1/16/07	139	26	28	30	N/A	28	2	65	4
1/22/07	145	18	18	21	N/A	19	2	44	4
2/2/07	156	15	15	13	N/A	14	1	33	3
2/9/07	163	13	11	11	N/A	12	1	27	3
2/19/07	173	7	7	7	N/A	7	0	16	1
2/23/2007	177	10	12	9	12	11	1	25	3
3/1/2007	183	N/A	N/A	8	7	7	0	17	1
3/2/2007	184	9	9	13	9	10	2	23	5
3/7/2007	189	8	8	8	13	9	2	21	5
3/9/2007	191	10	9	1	9	7	4	17	10
3/12/2007	194	8	9	10	8	8	1	20	2
3/16/2007	198	N/A	42	59	52	51	9	119	20
3/19/2007	201	40	50	43	30	41	8	95	19
3/23/2007	205	N/A	40	21	13	25	14	58	32
3/26/2007	208	11	10	19	12	13	4	30	9
3/30/2007	212	11	14	10	9	11	2	26	5
4/4/2007	217	26	10	10	17	16	8	37	18
4/9/2007	222	15	10	13	9	12	2	27	5
4/24/2007	237	8	50	11	11	20	20	47	46
4/27/2007	240	8	N/A	9	7	8	1	18	3
5/3/2007	246	8	8	4	8	7	2	16	5
5/14/2007	257	0	0	0	0	0	0	0	0
5/21/2007	264	0	0	0	0	0	0	0	0
5/29/2007	272	0	0	0	0	0	0	0	0
6/6/2007	280	0	0	0	0	0	0	0	0
6/12/2007	286	0	0	0	0	0	0	0	0
6/23/2007	297	0	0	0	0	0	0	0	0
7/6/2007	310	10	9	10	11	10	1	23	2
7/24/2007	328	14	13	16	11	14	2	32	5
8/28/2007	363	18	15	21	22	19	3	45	7
					Average (days 0-363):			40	
					Standard deviation (days 0-363):			65	
					Average (days 98-363):			37	
					Standard deviation (days 98-363):			37	

Table B-22: Total pilot scale fermenter effluent VFA concentrations.

VFA	Average (mg/L COD)	Standard deviation (mg/L COD)
Acetic	1420	333
Proprionic	763	245
Isobutyric	103	34
Butyric	204	111
Isovaleric	70	45
Valeric	70	67
Isocaproic	11	9
Hexanoic	2	11
Heptanoic	37	37
Sum	2680	
Maximum standard deviation	333	

Table B-23: Fermenter effluent SCOD concentrations.

Date	Day	Rep 1 SCOD (mg/L)	Rep 2 SCOD (mg/L)	Average (mg/L)	Maximum - Average (mg/L)
9/28/2006	29	6086	N/A	6086	0
9/28/2006	29	5567	5651	5609	42
3/26/2007	208	4466	4466	4466	0
3/30/2007	212	4110	4200	4155	45
4/4/2007	217	3944	4144	4044	100
4/9/2007	222	4361	4546	4453	92
4/24/2007	237	3619	3619	3619	0
4/27/2007	240	3666	3704	3685	19
5/3/2007	246	3883	3904	3894	10
5/14/2007	257	4040	3953	3996	43
5/21/2007	264	4811	5034	4923	111
5/29/2007	272	3988	4198	4093	105
6/6/2007	280	3749	3769	3759	10
6/23/2007	297	3681	3579	3630	51
7/6/2007	310	4129	N/A	4129	0
7/24/2007	328	3509	3569	3539	30
Average (days 0-363):				4255	
Standard Deviation (days 0-363):				725	
Average (days 98-363):				4028	
Standard Deviation (days 98-363):				390	

Table B-24: Pilot scale fermenter TSS concentrations.

Date	Day	Rep 1 TSS (mg/L)	Rep 2 TSS (mg/L)	Rep 3 TSS (mg/L)	Average TSS (mg/L)	Standard Deviation (mg/L)
9/2/2006	3	14800	13600	13900	14100	624
9/5/2006	6	12200	13600	N/A	12900	990
9/7/2006	8	15400	12000	15600	14333	2023
9/10/2006	11	11800	13000	11800	12200	693
9/18/2006	19	13400	13800	13600	13600	200

Date	Day	Rep 1 TSS (mg/L)	Rep 2 TSS (mg/L)	Rep 3 TSS (mg/L)	Average TSS (mg/L)	Standard Deviation (mg/L)
9/21/2006	22	7900	7800	7800	7833	58
9/24/2006	25	9800	10100	10300	10067	252
9/26/2006	27	2600	4300	4400	3767	1012
9/28/2006	29	15300	14400	14400	14700	520
9/30/2006	31	13400	14900	15700	14667	1168
10/3/2006	34	13600	13300	12600	13167	513
10/5/2006	36	12200	11000	11800	11667	611
10/8/2006	39	17800	19500	18700	18667	850
10/10/2006	41	14300	16100	14000	14800	1136
10/13/2006	44	19100	14300	13000	15467	3213
10/17/2006	48	12400	11300	12100	11933	569
10/24/2006	55	10300	10400	9800	10167	321
10/29/2006	60	15700	17400	17500	16867	1012
11/3/2006	65	18100	17400	18200	17900	436
11/6/2006	68	15100	14400	14100	14533	513
11/7/2006	69	11900	11100	16500	13167	2914
11/10/2006	72	16400	15300	15800	15833	551
11/13/2006	75	13100	13500	13100	13233	231
11/14/2006	76	10700	10100	12700	11167	1361
11/17/2006	79	17200	16300	17200	16900	520
11/28/2006	90	8600	11000	9100	9567	1266
12/5/2006	97	11000	10700	10800	10833	153
12/9/2006	101	15400	16600	17600	16533	1102
12/16/2006	108	15200	13600	12100	13633	1550
12/19/2006	111	15000	16300	15000	15433	751
12/22/2006	114	15700	15400	16400	15833	513
1/2/2007	125	17100	17400	18300	17600	624
1/8/2007	131	16700	15500	15500	15900	693
1/10/2007	133	13600	14000	13300	13633	351
1/12/2007	135	12600	12800	14200	13200	872
1/16/2007	139	12200	12200	11700	12033	289
1/19/2007	142	12600	13000	13000	12867	231
1/22/2007	145	13200	14800	13000	13667	987
1/23/2007	146	13500	13800	14600	13967	569
2/5/2007	159	11300	11900	12700	11967	702
2/9/2007	163	7600	7900	6800	7433	569
2/12/2007	166	12800	12800	12100	12567	404
2/19/2007	173	12100	14200	12200	12833	1185
2/21/2007	175	13000	14800	18100	15300	2587
3/1/2007	183	14900	14110	12700	13903	1114
3/2/2007	184	12500	12300	12300	12367	115
3/7/2007	189	14500	15300	17000	15600	1277
3/9/2007	191	17700	19900	19100	18900	1114
3/12/2007	194	16000	16700	16500	16400	361
3/14/2007	196	15500	13600	15200	14767	1021
3/19/2007	201	15200	13100	14300	14200	1054
3/23/2007	205	11000	12800	12300	12033	929
3/26/2007	208	14600	18500	18500	17200	2252
3/30/2007	212	11100	12900	14800	12933	1850

Date	Day	Rep 1 TSS (mg/L)	Rep 2 TSS (mg/L)	Rep 3 TSS (mg/L)	Average TSS (mg/L)	Standard Deviation (mg/L)
4/4/2007	217	13200	17700	13400	14767	2542
4/9/2007	222	11900	13200	N/A	12550	919
4/24/2007	237	11700	10800	11600	11367	493
4/27/2007	240	10100	10400	9500	10000	458
5/14/2007	257	11500	11100	13400	12000	1229
5/21/2007	264	11400	11400	11600	11467	115
5/29/2007	272	14000	18300	19700	17333	2970
6/6/2007	280	12900	12600	14000	13167	737
6/11/2007	285	15900	16000	17500	16467	896
6/23/2007	297	14400	14500	15100	14667	379
7/6/2007	310	16300	11100	10200	12533	3293
7/24/2007	328	14300	14800	16500	15200	1153
8/28/2007	363	19800	20000	20900	20233	586
	Average (days 0-363):				13709	
	Standard deviation (days 0-363):				2799	
	Average (days 98-363):				14111	
	Standard deviation (days 98-363):				2450	

Table B-25: Pilot scale fermenter VSS concentrations.

Date	Day	Rep 1 VSS (mg/L)	Rep 2 VSS (mg/L)	Rep 3 VSS (mg/L)	Average VSS (mg/L)	Standard Deviation (mg/L)
9/2/2006	3	12300	11100	11500	11633	611
9/5/2006	6	8300	9500	N/A	8900	849
9/7/2006	8	11300	8900	10700	10300	1249
9/10/2006	11	9300	9700	9000	9333	351
9/18/2006	19	9000	8800	9500	9100	361
9/21/2006	22	5400	5100	4700	5067	351
9/24/2006	25	7400	8200	8200	7933	462
9/26/2006	27	3500	5000	2800	3767	1124
9/28/2006	29	11600	10900	10300	10933	651
9/30/2006	31	11200	12200	13100	12167	950
10/3/2006	34	9500	9100	9900	9500	400
10/5/2006	36	9700	8700	9500	9300	529
10/8/2006	39	12700	14700	14400	13933	1079
10/10/2006	41	13000	14100	12500	13200	819
10/13/2006	44	15000	10600	9900	11833	2765
10/17/2006	48	10800	9700	10000	10167	569
10/24/2006	55	8100	8400	7600	8033	404
10/29/2006	60	12700	13600	13700	13333	551
11/3/2006	65	13700	12900	14100	13567	611
11/6/2006	68	10100	10100	9800	10000	173
11/7/2006	69	10800	9400	9000	9733	945
11/10/2006	72	11600	10300	10800	10900	656
11/13/2006	75	10200	10700	11000	10633	404
11/14/2006	76	9500	10300	11100	10300	800
11/17/2006	79	12600	12200	11500	12100	557
11/28/2006	90	8400	9900	8600	8967	814

Date	Day	Rep 1 VSS (mg/L)	Rep 2 VSS (mg/L)	Rep 3 VSS (mg/L)	Average VSS (mg/L)	Standard Deviation (mg/L)
12/5/2006	97	10700	10400	10600	10567	153
12/9/2006	101	13000	13500	14200	13567	603
12/16/2006	108	12100	10700	9900	10900	1114
12/19/2006	111	12300	13400	12000	12567	737
12/22/2006	114	13700	13400	13800	13633	208
1/2/2007	125	15400	16000	16200	15867	416
1/8/2007	131	14300	13000	13100	13467	723
1/10/2007	133	11800	12400	12100	12100	300
1/12/2007	135	10400	10500	12000	10967	896
1/16/2007	139	9800	10600	9300	9900	656
1/19/2007	142	10200	10500	10800	10500	300
1/22/2007	145	11200	12000	10300	11167	850
1/23/2007	146	12200	12200	12900	12433	404
2/5/2007	159	9700	10300	10700	10233	503
2/9/2007	163	9000	9600	8600	9067	503
2/12/2007	166	12000	11800	11200	11667	416
2/19/2007	173	10400	11600	10300	10767	723
2/21/2007	175	10800	12000	15300	12700	2330
3/1/2007	183	12300	11410	10300	11337	1002
3/2/2007	184	10600	11000	10700	10767	208
3/7/2007	189	12300	13000	14500	13267	1124
3/9/2007	191	14000	15900	15100	15000	954
3/12/2007	194	13200	13500	13400	13367	153
3/14/2007	196	12200	10700	12400	11767	929
3/19/2007	201	13800	10800	11200	11933	1629
3/23/2007	205	9400	10400	10000	9933	503
3/26/2007	208	10300	13500	13400	12400	1819
3/30/2007	212	9500	11300	12800	11200	1652
4/4/2007	217	11500	14500	11500	12500	1732
4/9/2007	222	10400	12000	N/A	11200	1131
4/24/2007	237	9700	9100	9800	9533	379
4/27/2007	240	9300	9900	8600	9267	651
5/14/2007	257	9400	9100	10300	9600	624
5/21/2007	264	9200	8800	8900	8967	208
5/29/2007	272	10700	13300	14800	12933	2074
6/6/2007	280	9700	9300	10600	9867	666
6/11/2007	285	13400	13900	14600	13967	603
6/23/2007	297	11700	11500	12100	11767	306
7/6/2007	310	12900	8800	8500	10067	2458
7/24/2007	328	12300	12800	14100	13067	929
8/28/2007	363	16100	16900	17400	16800	656
	Average (days 0-363):				11152	
	Standard deviation (days 0-363):				2183	
	Average (days 98-363):				11800	
	Standard deviation (days 98-363):				1832	

B.3 DETERMINING THE SOURCE AND AVAILABILITY OF SCOD FOR DENITRIFICATION DURING THE FINAL ANOXIC ZONE

Table B-26: SCOD loss during aerobic zone to determine if VFA was available in the final anoxic zone for denitrification.

DO (mg/L)	SCOD removed during aerobic phase cycle (mg/L)	SCOD loss during the first 2.1 hrs. of aerobic zone (40% of aerobic zone) (mg/L)	Percent SCOD loss (of total SCOD removed) during the first 2.1 hrs. of aerobic zone (40% of aerobic zone)
2.0	68.9	38.4	56%
1.8	N/A	N/A	N/A
1.6	100.4	73.3	73%
1.5	64.0	55.5	87%
1.4	89.5	73.6	82%
1.3	55.7	55.7	100%
1.2	70.6	34.2	49%
1.1	87.6	77.8	89%
1.0	104.1	81.7	79%
0.9	81.8	61.9	76%
0.8	78.6	77.8	99%
		Average (%):	79%
		Standard deviation (%):	17%

Table B-27: Denitrification rates from cross cycles.

Date	DO set point	NO_3^- reduced during final anoxic zone	Denitrification rate	Denitrification rate
	mg/L	mg/L-N	mg/L-N day^{-1}	mg/L-N day^{-1} $gVSS^{-1}$
4/20/2007	2	4.9	-110.24	-10.84
4/30/2007	1.8	7.2	-106.35	-9.82
5/8/2007	1.6	6.4	-92.561	-11.82
5/16/2007	1.5	7.7	-111.46	-14.38
5/23/2007	1.4	7.5	-124.72	-16.27
5/31/2007	1.3	6.6	-103.89	-12.77
6/20/2007	1.2	4.3	-142.36	-16.12
7/9/2007	1.1	4.4	-152.27	-19.52
7/18/2007	1.0	3.9	-133.61	-15.91
7/28/2007	0.9	3.1	-96.121	-8.43
8/7/2007	0.8	2.3	-81.164	-8.06
Average:		5.3		-13.09
Standard deviation:		1.9		3.67

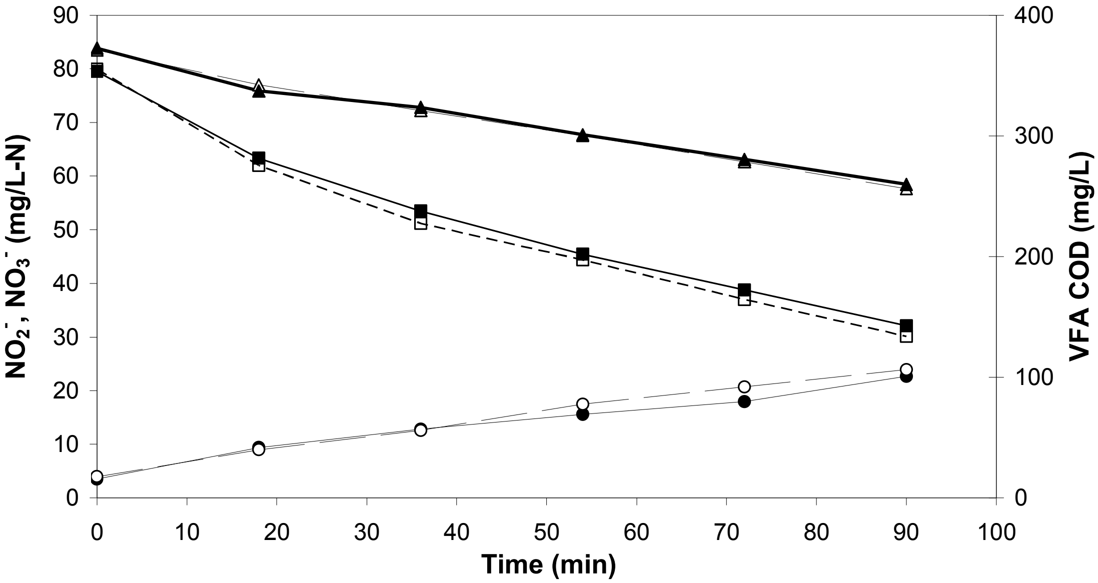

Figure B-1: Typical denitrification batch test profile showing approximately 85 mg/L NO_3^--N (□,■) added at time = 0 min. Acetate (△, ▲) was spiked at a concentration of approximately 350 mg/L COD. NO_2^--N (○, ●) was found to accumulate during the test.

Table B-28: Denitrification batch tests raw data (raw data in Tables B-31-36).

Experiment 3/21/2007 (biological duplicates)	NO_2^- Consumption rate (mg/L N min^{-1})		NO_3^- Consumption rate (mg/L N min^{-1})		NO_2^- Accumulation rate (mg/L N min^{-1})		VFA Consumption rate (mg/L COD min^{-1})	
100 mg/L NO_2^-	0.10	0.11	--	--	--	--	0.52	0.68
100 mg/L NO_3^-	--	--	0.28	0.27	0.20	0.22	2.33	2.25
100 mg/L NO_2^- + 100 mg/L NO_3^-	--	--	0.26	0.25	0.21	0.19	1.69	1.47
6/12/2007 (biological duplicates)								
100 mg/L NO_2^-	0.14	0.13	--	--	--	--	0.56	0.77
100 mg/L NO_3^-	--	--	0.47	0.42	0.38	0.33	2.25	2.03

Date	VSS-Rep 1 (mg/L)	VSS-Rep 2 (mg/L)	VSS-Rep 3 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)
3/21/2007	10000	9550	10250	9933	355
6/12/2007	9000	8900	8400	8767	321

Table B-29: Denitrification batch test rates normalized to VSS concentration.

Experiment 3/21/2007 (duplicates averaged)	NO_2^- Consumption rate (mg N $gVSS^{-1}$ day^{-1})	NO_3^- Consumption rate (mg N $gVSS^{-1}$ day^{-1})	NO_2^- Accumulation rate (mg N $gVSS^{-1}$ day^{-1})	Theoretical NO_2^- Consumption rate (mg N $gVSS^{-1}$ day^{-1})
100 mg/L NO_2^-	14.9	--	--	--
100 mg/L NO_3^-	--	39.9	30.4	9.6
100 mg/L NO_2^- + 100 mg/L NO_3^-	--	37.1	29.3	7.8
6/12/2007 (duplicates averaged)				
100 mg/L NO_2^-	22.0	--	--	--
100 mg/L NO_3^-	--	72.9	58.8	14.2

Table B-30: COD:N consumption ratios for denitrification batch tests.

Experiment 3/21/2007 (duplicates averaged)	VFA Consumption rate (mg COD $gVSS^{-1}$ day^{-1})	COD:NO_2^- rate ratio g N:g COD	COD:NO_3^- rate ratio g N:g COD
100 mg/L NO_2^-	86.8	5.8	
100 mg/L NO_3^-	332.2		8.3
100 mg/L NO_2^- + 100 mg/L NO_3^-	228.8		6.2
6/12/2007 (duplicates averaged)			
100 mg/L NO_2^-	109.0	5.0	
100 mg/L NO_3^-	351. 4		4.8

Table B-31: NO_2^- data for denitrification batch tests performed on day 203.

		Date	Time (min)	Rep 1 (mg/L-N)	Rep 2 (mg/L-N)	Average (mg/L-N)	Maximum- Average (mg/L-N)
3/21/2007	A	3/21/2007	0	104	105	104	0.2
		3/21/2007	18	103	102	103	0.3
		3/21/2007	36	100	99	100	0.5
		3/21/2007	54	98	98	98	0.1
		3/21/2007	72	97	97	97	0.0
		3/21/2007	90	95	94	94	0.2
3/21/2007	B	3/21/2007	0	105	105	105	0.2
		3/21/2007	18	102	103	103	0.2
		3/21/2007	36	101	101	101	0.2
		3/21/2007	54	99	100	100	0.1
		3/21/2007	72	97	98	98	0.1
		3/21/2007	90	97	96	96	0.4
3/21/2007	C	3/21/2007	0	4	3	4	0.1
		3/21/2007	18	9	9	9	0.0
		3/21/2007	36	13	13	13	0.0
		3/21/2007	54	16	16	16	0.0
		3/21/2007	72	18	18	18	0.1
		3/21/2007	90	23	22	23	0.3
3/21/2007	D	3/21/2007	0	4	4	4	0.0
		3/21/2007	18	9	9	9	0.1
		3/21/2007	36	13	13	13	0.0
		3/21/2007	54	17	17	17	0.0
		3/21/2007	72	21	21	21	0.1
		3/21/2007	90	24	24	24	0.3
3/21/2007	E	3/21/2007	0	N/A	N/A	N/A	N/A
		3/21/2007	18	N/A	N/A	N/A	N/A
		3/21/2007	36	N/A	N/A	N/A	N/A
		3/21/2007	54	N/A	N/A	N/A	N/A
		3/21/2007	72	N/A	N/A	N/A	N/A
		3/21/2007	90	N/A	N/A	N/A	N/A
3/21/2007	F	3/21/2007	0	102	102	102	0.3
		3/21/2007	18	107	108	107	0.3
		3/21/2007	36	110	109	109	0.4
		3/21/2007	54	111	112	112	0.4
		3/21/2007	72	115	114	114	0.1
		3/21/2007	90	117	117	117	0.2

Table B-32: NO_2^- data for denitrification batch tests performed on day 286 (Zero concentration indicates not detected).

		Date	Time (min)	Rep 1 (mg/L-N)	Rep 2 (mg/L-N)	Rep 3 (mg/L-N)	Rep 4 (mg/L-N)	Average (mg/L-N)	Standard deviation (mg/L-N)
6/12/2007	A	6/12/2007	0	108	108	N/A	N/A	108	0.3
		6/12/2007	18	106	107	111	108	108	2.2
		6/12/2007	36	104	104	104	105	104	0.7
		6/12/2007	54	99	100	102	103	101	1.5
		6/12/2007	72	97	98	99	100	99	1.4
		6/12/2007	90	97	97	96	97	97	0.4
6/12/2007	B	6/12/2007	0	104	106	106	103	105	1.8
		6/12/2007	18	103	103	N/A	N/A	103	0.1
		6/12/2007	36	97	98	102	100	99	2.1
		6/12/2007	54	97	98	97	99	98	0.9
		6/12/2007	72	93	93	94	95	94	0.9
		6/12/2007	90	93	94	94	95	94	0.5
6/12/2007	C	6/12/2007	0	3	0	3	3	3	1.7
		6/12/2007	18	10	10	10	10	10	0.1
		6/12/2007	36	20	20	20	20	20	0.2
		6/12/2007	54	25	25	25	25	25	0.3
		6/12/2007	72	32	31	31	31	31	0.5
		6/12/2007	90	38	38	38	38	38	0.1
6/12/2007	D	6/12/2007	0	3	3	3	3	3	0.1
		6/12/2007	18	10	10	10	10	10	0.1
		6/12/2007	36	20	19	19	19	19	0.8
		6/12/2007	54	22	22	22	23	22	0.2
		6/12/2007	72	27	28	28	28	28	0.4
		6/12/2007	90	33	34	34	34	33	0.2
6/12/2007	E	6/12/2007	0	3	4	2	3	3	0.5
		6/12/2007	18	10	10	9	9	10	0.3
		6/12/2007	36	18	18	20	19	19	0.9
		6/12/2007	54	22	22	23	23	23	0.6
		6/12/2007	72	27	27	27	27	27	0.4
		6/12/2007	90	33	33	32	33	33	0.5
6/12/2007	F	6/12/2007	0	2	3	3	2	3	0.2
		6/12/2007	18	8	8	8	8	8	0.1
		6/12/2007	36	17	17	17	16	17	0.2
		6/12/2007	54	20	20	20	20	20	0.2
		6/12/2007	72	24	24	23	24	24	0.5
		6/12/2007	90	29	29	28	28	28	0.8

Table B-33: NO_3^- data for denitrification batch tests performed on day 203 (Zero concentration indicates not detected).

		Date	Time (min)	Rep 1 (mg/L-N)	Rep 2 (mg/L-N)	Average (mg/L-N)	Maximum- Average (mg/L-N)
3/21/2007	A	3/21/2007	0	0	0	0	0.0
		3/21/2007	18	0	0	0	0.0
		3/21/2007	36	0	0	0	0.0
		3/21/2007	54	0	0	0	0.0
		3/21/2007	72	0	0	0	0.0
		3/21/2007	90	0	0	0	0.0
3/21/2007	B	3/21/2007	0	0	0	0	0.0
		3/21/2007	18	0	0	0	0.0
		3/21/2007	36	0	0	0	0.0
		3/21/2007	54	0	0	0	0.0
		3/21/2007	72	0	0	0	0.0
		3/21/2007	90	0	0	0	0.0
3/21/2007	C	3/21/2007	0	83	83	83	0.0
		3/21/2007	18	77	77	77	0.2
		3/21/2007	36	72	72	72	0.1
		3/21/2007	54	68	67	68	0.1
		3/21/2007	72	63	62	63	0.3
		3/21/2007	90	58	58	58	0.0
3/21/2007	D	3/21/2007	0	84	84	84	0.3
		3/21/2007	18	76	76	76	0.3
		3/21/2007	36	73	73	73	0.1
		3/21/2007	54	68	68	68	0.1
		3/21/2007	72	63	63	63	0.1
		3/21/2007	90	59	58	58	0.1
3/21/2007	E	3/21/2007	0	82	83	82	0.0
		3/21/2007	18	73	72	72	0.4
		3/21/2007	36	66	66	66	0.2
		3/21/2007	54	62	65	63	1.1
		3/21/2007	72	61	60	60	0.5
		3/21/2007	90	59	55	57	2.0
3/21/2007	F	3/21/2007	0	83	83	83	0.1
		3/21/2007	18	77	78	77	0.3
		3/21/2007	36	73	73	73	0.3
		3/21/2007	54	68	69	69	0.2
		3/21/2007	72	64	64	64	0.0
		3/21/2007	90	60	60	60	0.1

Table B-34: NO_3^- data for denitrification batch tests performed on day 286 (Zero concentration indicates not detected).

		Date	Time (min)	Rep 1 mg/L-N	Rep 2 mg/L-N	Average mg/L-N	Maximum- Average mg/L-N
6/12/2007	A	6/12/2007	0	0	0	0	0.0
		6/12/2007	18	0	0	0	0.1
		6/12/2007	36	0	0	0	0.1
		6/12/2007	54	0	0	0	0.1
		6/12/2007	72	0	0	0	0.1
		6/12/2007	90	0	0	0	0.0
6/12/2007	B	6/12/2007	0	0	0	0	0.0
		6/12/2007	18	0	0	0	0.0
		6/12/2007	36	0	0	0	0.0
		6/12/2007	54	0	0	0	0.1
		6/12/2007	72	0	0	0	0.0
		6/12/2007	90	0	0	0	0.1
6/12/2007	C	6/12/2007	0	95	96	96	0.4
		6/12/2007	18	90	90	90	0.3
		6/12/2007	36	78	78	78	0.1
		6/12/2007	54	73	73	73	0.1
		6/12/2007	72	63	64	64	0.1
		6/12/2007	90	53	53	53	0.0
6/12/2007	D	6/12/2007	0	92	93	92	0.2
		6/12/2007	18	87	87	87	0.0
		6/12/2007	36	75	76	76	0.2
		6/12/2007	54	71	71	71	0.0
		6/12/2007	72	64	60	62	2.0
		6/12/2007	90	56	56	56	0.0
6/12/2007	E	6/12/2007	0	108	109	109	0.3
		6/12/2007	18	102	102	102	0.2
		6/12/2007	36	90	90	90	0.1
		6/12/2007	54	86	86	86	0.1
		6/12/2007	72	79	79	79	0.0
		6/12/2007	90	70	70	70	0.2
6/12/2007	F	6/12/2007	0	100	100	100	0.2
		6/12/2007	18	94	95	94	0.2
		6/12/2007	36	84	84	84	0.1
		6/12/2007	54	80	81	80	0.0
		6/12/2007	72	73	73	73	0.0
		6/12/2007	90	66	66	66	0.3

Table B-35: Acetic acid data for denitrification batch tests performed on day 203 assuming 1.07 g COD per g acetate.

	Date	Time (min)	Rep 1 mg/L	Rep 2 mg/L	Rep 3 mg/L	Rep 4 mg/L	Average mg/L	Average COD mg/L	Standard deviation mg/L COD
A	3/21/2007	0	132	128	129	N/A	130	139	2
	3/21/2007	18	121	116	117	N/A	118	126	2
	3/21/2007	36	106	107	108	107	107	115	1
	3/21/2007	54	99	96	97	98	98	104	1
	3/21/2007	72	90	91	92	92	91	97	1
	3/21/2007	90	88	87	87	86	87	93	1
B	3/21/2007	0	137	135	136	137	136	146	1
	3/21/2007	18	109	113	113	N/A	112	119	2
	3/21/2007	36	102	101	101	101	101	108	0
	3/21/2007	54	91	93	92	89	91	98	2
	3/21/2007	72	82	83	80	83	82	88	1
	3/21/2007	90	76	75	75	77	76	81	1
C	3/21/2007	0	336	327	334	331	332	355	4
	3/21/2007	18	263	250	253	263	257	275	7
	3/21/2007	36	212	209	212	217	213	227	3
	3/21/2007	54	183	182	188	184	184	197	3
	3/21/2007	72	159	150	152	154	154	164	4
	3/21/2007	90	128	126	122	125	125	134	3
D	3/21/2007	0	319	330	340	332	330	353	9
	3/21/2007	18	266	261	266	259	263	281	3
	3/21/2007	36	219	224	225	220	222	238	3
	3/21/2007	54	189	188	185	192	189	202	3
	3/21/2007	72	160	166	158	159	161	172	4
	3/21/2007	90	136	137	134	126	133	143	5
E	3/21/2007	0	492	478	502	491	491	525	10
	3/21/2007	18	431	435	435	447	437	468	8
	3/21/2007	36	416	396	416	407	409	437	10
	3/21/2007	54	387	380	375	391	384	410	8
	3/21/2007	72	353	366	347	349	354	378	9
	3/21/2007	90	348	335	355	350	347	371	9
F	3/21/2007	0	497	483	485	474	485	519	10
	3/21/2007	18	442	445	430	N/A	439	470	9
	3/21/2007	36	411	414	N/A	402	409	438	7
	3/21/2007	54	401	392	399	397	397	425	4
	3/21/2007	72	378	367	N/A	378	374	401	7
	3/21/2007	90	N/A	351	355	352	353	377	2

Table B-36: Acetic acid data for denitrification batch tests performed on day 286 assuming 1.07 g COD per g acetate.

	Date	Time (min)	Rep 1	Rep 2	Rep 3	Rep 4	Average	Average COD	Standard deviation
			mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L COD
A	6/12/2007	0	105	103	N/A	N/A	104	111	2
	6/12/2007	18	86	87	N/A	N/A	86	92	1
	6/12/2007	36	74	75	N/A	N/A	75	80	1
	6/12/2007	54	74	73	N/A	N/A	73	78	1
	6/12/2007	72	63	60	N/A	N/A	62	66	3
	6/12/2007	90	53	54	N/A	N/A	54	57	1
B	6/12/2007	0	104	106	N/A	N/A	105	112	2
	6/12/2007	18	85	83	N/A	N/A	84	89	2
	6/12/2007	36	59	59	N/A	N/A	59	63	0
	6/12/2007	54	54	55	N/A	N/A	55	59	1
	6/12/2007	72	48	46	N/A	N/A	47	50	2
	6/12/2007	90	36	38	N/A	N/A	37	40	1
C	6/12/2007	0	302	306	N/A	N/A	304	325	2
	6/12/2007	18	264	268	N/A	N/A	266	285	3
	6/12/2007	36	196	200	N/A	N/A	198	212	3
	6/12/2007	54	180	179	N/A	N/A	180	192	1
	6/12/2007	72	147	147	N/A	N/A	147	157	0
	6/12/2007	90	117	112	N/A	N/A	115	123	4
D	6/12/2007	0	291	292	N/A	N/A	292	312	1
	6/12/2007	18	252	254	N/A	N/A	253	271	2
	6/12/2007	36	195	197	N/A	N/A	196	210	2
	6/12/2007	54	178	176	N/A	N/A	177	189	1
	6/12/2007	72	146	147	N/A	N/A	147	157	1
	6/12/2007	90	120	120	N/A	N/A	120	128	0
E	6/12/2007	0	793	786	N/A	N/A	789	845	6
	6/12/2007	18	907	813	N/A	N/A	860	920	71
	6/12/2007	36	820	774	N/A	N/A	797	853	35
	6/12/2007	54	759	728	N/A	N/A	744	796	23
	6/12/2007	72	791	764	N/A	N/A	777	832	20
	6/12/2007	90	751	742	N/A	N/A	746	798	7
F	6/12/2007	0	822	833	N/A	N/A	827	885	8
	6/12/2007	18	693	673	N/A	N/A	683	731	15
	6/12/2007	36	766	769	N/A	N/A	768	821	2
	6/12/2007	54	745	753	N/A	N/A	749	802	5
	6/12/2007	72	706	702	N/A	N/A	704	753	3
	6/12/2007	90	714	713	N/A	N/A	714	764	1

B.4 SIMULTANEOUS NITRIFICATION-DENITRIFICATION (SND) WAS MOST APPARENT AT DO LEVELS BELOW 1.3 MG/L

Table B-37: Maximum percent of removed TAN measured as NO_2^- and $NO_2^- + NO_3^-$ during the aerobic phase.

DO (mg/L)	TAN removed during aerobic phase (mg/L)	Maximum NO_2^--N during the aerobic phase (mg/L)	Maximum % of TAN removed converted to NO_2^- during aerobic phase	Maximum NO_2^--N + NO_3^--N during the aerobic phase (mg/L)	Maximum % of TAN removed converted to $NO_2^- + NO_3^-$
2	5.4	0.7	13%	5.0	93%
1.8	6.4	1.0	16%	7.7	119%
1.6	8.0	1.8	23%	10.5	130%
1.5	12.0	2.7	22%	11.5	96%
1.4	8.9	3.6	40%	7.7	87%
1.3	8.5	3.6	42%	7.6	90%
1.2	6.3	1.4	22%	4.4	70%
1.1	9.8	2.9	29%	4.8	49%
1	7.1	1.8	26%	4.1	58%
0.9	7.2	1.1	15%	3.1	44%
0.8	4.1	0.9	22%	2.4	58%

The following equation was used to determine the COD:N ratio required for denitrification:

$$\frac{\Delta S}{\Delta oxidized - N} = \frac{A(1 + b_H\theta_c)}{1 + (b_H\theta_c) - Y_H(1 + f_D b_H \theta_c)} \qquad \text{Equation B- 1}$$

Table B-38: Denitrification equation and calculations.

Description	Variable	Value
heterotrophic decay rate	b_H	0.18 day^{-1} [1]
Anoxic SRT	θ_c	3.5 days[2]
heterotrophic growth yield	Y_H	0.6 g COD / g COD[1]
debris fraction of active biomass	f_D	0.2 mg debris COD/mg biomass COD[1]
Coefficient	A	1.17 for NO_2^- and 2.86 for NO_3^-
rbCOD:N required to denitrify via NO_2^-	$\Delta S:\Delta NO_2^- -N$	**2.00 g COD / g NO_2^-–N**
rbCOD:N required to denitrify via NO_3^-	$\Delta S:\Delta NO_3^- -N$	**4.88 g COD / g NO_3^-–N**

[1] (Grady et al., 1999)
[2] Actual system anoxic SRT

Table B-39: Carbon source:N available for denitrification during the aerobic phase of each cross cycle.

DO (mg/L)	TAN removed during aerobic phase (mg/L-N)	COD removed during aerobic phase cycle (mg/L)	COD:N-removed (mg:mg N)
2	5.37	69	13
1.8	6.45	N/A	N/A
1.6	8.04	100	12
1.5	11.98	64	5
1.4	8.85	90	10
1.3	8.47	56	7
1.2	6.34	71	11
1.1	9.78	88	9
1	7.06	104	15
0.9	7.16	82	11
0.8	4.14	79	19

B.4.1 Nitrogen balance, N assimilated into biomass.

Assuming a heterotrophic yield, Y_H, of 0.6 g biomass COD formed per g COD consumed and COD consumed in the form of typical domestic wastewater ($C_{10}H_{19}O_3N$, 1.99 gCOD/g substrate), the following stoichiometric equation (normalized per mole of biomass ($C_5H_7O_2N$) formed) was determined for the oxidation of COD (Grady et al., 1999).

$0.67\ C_{10}H_{19}O_3N + 3.33\ O_2 + 0.33\ HCO_3^- + 0.33\ NH_4^+ \rightarrow$ Equation B- 2
$C_5H_7O_2N + 3.67\ H_2O + 2\ CO_2$
Mol NH_4^+: Mol $C_{10}H_{19}O_3N$ consumed = 0.33/0.67 = 0.5

g $C_{10}H_{19}O_3N$ per Mol $C_{10}H_{19}O_3N$ = 201 = 400 g COD per Mol $C_{10}H_{19}O_3N$ (assuming 1.99 g COD per g $C_{10}H_{19}O_3N$, Grady et al. (1999))

g N per Mol NH_4^+ = 14

Therefore, **0.018 mg N** is assimilated into heterotrophic biomass per mg COD consumed.

Likewise, the mg N required for autotrophic growth was also calculated. NH_4^+-N is used as the N source for autotrophic biomass ($C_5H_7O_2N$) growth according to the following equation assuming an autotrophic yield of 0.24 g biomass COD formed per g NH_4^+-N oxidized (Grady et al., 1999).

$20.8\ NH_4^+ + NH_4^+\ (cell) + 15.8\ O_2 + 4\ CO_2 \rightarrow$ Equation B- 3

$C_5H_7O_2N + 20.8\ NO_3^- + 19.8\ H_2O$

Mol NH_4^+ per Mol $C_5H_7O_2N$ formed = 1/20.8 = **0.048** = g N assimilated into autotrophic biomass per g TAN oxidized.

Table B-40: N assimilated into heterotrophic and autotrophic biomass based on ratios calculated above.

DO (mg/L)	Initial TAN concentration - TAN oxidized during aerobic zone (mg/L-N)	SCOD removed during aerobic phase cycle (mg/L)	mg/L N used for heterotrophic biomass growth based on SCOD removal	TAN available for autotrophic growth (Initial TAN - N used for heterotrophic growth)	mg/L N used for autotrophic biomass growth based on TAN removal
2	5.37	69	1.20	4.16	0.20
1.8	6.45	N/A	0.00	6.45	0.31
1.6	8.04	100	1.76	6.29	0.30
1.5	11.98	64	1.12	10.86	0.52
1.4	8.85	90	1.57	7.29	0.35
1.3	8.47	56	0.97	7.49	0.36
1.2	6.34	71	1.24	5.10	0.24
1.1	9.78	88	1.53	8.24	0.40
1	7.06	104	1.82	5.24	0.25
0.9	7.16	82	1.43	5.73	0.27
0.8	4.14	79	1.38	2.77	0.13

B.4.2 Nitrogen balance, gaseous N products.

Table B-41: N_2 gas analysis measured on day 358 when DO during aerobic phase = 0.8 mg/L.

Sample	Concentration (g/m^3 N_2)	% of lab air
7:45PM A	891	100%
7:45PM B	882	99%
8:30 PM A	895	100%
8:30 PM B	890	100%
Average	889	100%
Stdev	5.8	1%

Table B-42: NO_x samples measured.

	Measured		Calculated
Sample	NO (ppb)	NO_x (ppb)	NO_2 (ppb)
Lab air	1	4.5	3.5
7:45:00 PM (31% of aerobic zone)	13	55	42
8:30:00 PM (45% of aerobic zone)	25	31	6
Average (ppb)	19	43	24

Table B-43: N_2O measurements.

Sample	ppm	g/m^3	peak area
1000 ppm std	1000	2.5	15161
500 ppm std	500	1.2	6044
100 ppm std	100	0.2	986
7:45PM A			N/A
8:30 PM A			N/A

To determine if the measured N_2 values were within sensitivity range of the N_2 analysis, a theoretical mass flow of N_2 produced by the reactor was calculated for a worst case scenario. Assuming that all initial TAN in the cross cycles where SND was most likely occurring (DO 0.8 – 1.2 mg/L) was subject to SND during the aerobic zone, an average of 6.9 ± 2.0 mg/L TAN would have been converted to N_2 during an average time of 3.2 ± 0.7 hours. Using the flow rate of the compressor (1.83 m^3/hr), the worst case average N_2 mass flow rate was calculated to be 0.16 g N_2 hr^{-1} or 0.01 % of the mass flow of atmospheric N_2 passing through the reactor (1632 g N_2 hr^{-1} assuming an N_2 content of atmospheric air of 78% or 892.7 g/m^3). This calculated production of possible N_2 produced is less than the detection limit of the N_2 gas analysis method. Furthermore, the theoretical worst case N_2 produced by the reactor (0.16 g N_2 hr^{-1}) was within the range of standard deviation of the measured concentration of N_2 during the aerobic zone (889.4 ± 5.8 g/m^3) of atmospheric air. Therefore, the N_2 measurements were inconclusive as to the production of N_2 during the aerobic zone of the N removal reactor.

APPENDIX C Nitrification Inhibition by fermented dairy manure: Identifying the presence of an inhibitor and its effect on AOB kinetic parameters

C.1 RESPIROMETRIC NITRIFYING INHIBITION TESTS.

Oxygen uptake rate (OUR) was measured using N removal reactor biomass pellets resuspended in various dilutions of fermenter supernatant on day 166 of operation. The objective of the test was to investigate the presence of a nitrification inhibitor in the fermenter supernatant. Specifically, fermenter supernatant dilutions of 1:3, 1:6, 1:12, and 1:30 (1:x is one part fermenter supernatant into x total parts) were tested. The test was conducted in a 300 mL BOD bottle with 100 mL of centrifuged, pelleted N removal reactor biomass with a mixed liquor volatile suspended solids (MLVSS) concentration of 10,500 mg/L. The N removal reactor biomass was sampled from the pilot scale reactor and then incubated in the laboratory for up to 8 hours in a completely mixed container with residual TAN and cycled aeration at a target DO of 2 mg/L to mimic the conditions in the pilot scale reactor. TAN was spiked to 100 mg-N/L and pH was measured at the beginning and end of each test to ensure that it was in the range of 7 to 7.5 to minimize the effects of free TAN inhibition on ammonia oxidizing bacteria (1-10 mg/L TAN (Anthonisen et al., 1976)). The SOUR test was run by measuring the DO over time, thus acquiring the rate of oxygen consumption. The oxygen uptake rate for the mixed liquor was determined in triplicate using Orion model 97-08 oxygen electrodes (Orion Research, Inc., Beverly, MA) connected to a data acquisition system. All OUR tests ran for 7 to 10 minutes and all DO was consumed in that timeframe. The OUR was performed and calculated according to section 2710 B of Standard Methods (APHA, 1998) and SOUR was calculated by dividing the OUR by the MLVSS concentration (measured raw, then adjusted based on dilutions incurred during the OUR test). Assays for each biomass/fermenter dilution condition were performed using two procedures: once with and once without the nitrification inhibitor allyl thiourea (ATU) spiked to a final concentration of 2 mg/L (Young, 1973). For mixed liquors with nitrifying activity, the slope of bioassays spiked with ATU are less than for bioassays without a nitrification inhibitor. The nitrifying activity of the N removal reactor biomass was calculated as the difference in slope between the two trials and is referred to as the nitrifying SOUR (nSOUR). If the contents of the fermenter effluent do not interfere with nitrification, the nitrifying activity of the N removal reactor biomass should not change as the fermented solution is diluted further. However, if the fermenter effluent contains one or more constituents that interfere with nitrification, an increase in nSOUR will be observed as the fermenter supernatant is further diluted. Such a scenario would indicate that a nitrification inhibitor is present.

The experiment was repeated by doing triplicate assays with mixed liquor collected on day 184, with minor modifications. The VSS of the N removal reactor mixed liquor was 10,800 mg/L. The nitrification inhibitor was changed to 10 mg/L of 2-chloro-6-(trichloro methyl) pyridine (TCMP) per section 5210 B.*4e6* of Standard Methods (APHA, 1998), in order to avoid possible interferences that might otherwise interact with ATU (Kelly et al., 2004)

The lowest fermenter supernatant dilution on days 166 and 184 were 1:3 and 1:1, respectively. Both of these dilutions produced results that were the opposite of what was expected. The OUR for the batches with ATU (inhibited nitrification) was actually greater than the OUR for the batch without ATU which yield a negative value for nSOUR (Tables C-2 and C-3). This suggests that the presence of ATU actually increased the nitrifying activity. Past research experience in our laboratory has shown that ATU and TCMP can couple with certain toxins and actually remove the inhibitory effect ((Kelly, 2005; Kelly et al., 2004) which was witnessed during these tests. Additionally, nitrifying activity increased as the fermenter supernatant became more dilute thus confirming the presence of an inhibitor in dairy waste (Figure C-1). This justified continuing additional experiments to detect a nitrification inhibitor; however, further tests were done using the nitrite generation rate assay described in Section 4.

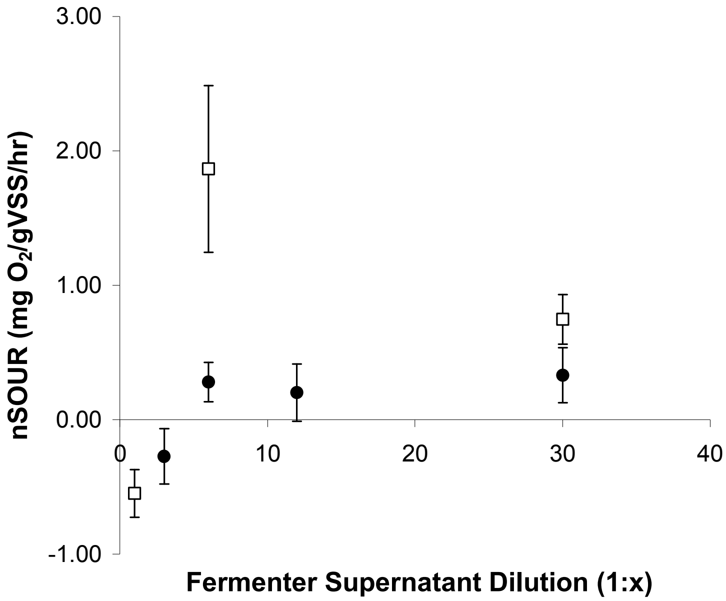

Figure C-1: nSOUR (SOUR accounting for nitrification) for experiments conducted on day 166 (□) and day 184 (●) showed that nitrifying activity increased with increasing values of fermenter supernatant.

C.1.1 Raw data for respirometric nitrifying inhibition tests

Table C-1: VSS concentrations for SOUR batch experiments.

Date	Day	Rep 1 VSS (mg/L)	Rep 2 VSS (mg/L)	Rep 3 VSS (mg/L)	Average (mg/L)	Standard Deviation (mg/L)
2/12/2007	166	3400	3667	3433	3500	145
3/2/2007	184	3233	3633	3900	3589	336

Table C-2: SOUR and nSOUR values for day 166 (ATU used as nitrification inhibitor).

SOUR for trials with ATU (No Nitrification)

Fermenter supernatant dilution (1:x)	mg O_2 consumed $gVSS^{-1}$ hr^{-1} 3	6	12	30
A	4.01	4.11	3.71	3.28
B	3.68	4.10	3.50	3.76
C	3.56	3.76	3.68	3.56
Average	3.751	3.992	3.629	3.533
Stdev	0.235	0.201	0.114	0.244

SOUR for trials without ATU (Nitrification)

Fermenter supernatant dilution (1:x)	mg O_2 consumed $gVSS^{-1}$ hr^{-1} 3	6	12	30
A	3.34	4.14	3.83	3.57
B	3.30	4.44	3.48	4.07
C	3.79	4.23	4.18	3.94
Average	3.477	4.271	3.829	3.863
Stdev	0.271	0.156	0.350	0.259

SOUR accounting for Nitrification (SOUR Difference) - nSOUR

Fermenter supernatant dilution (1:x)	mg O_2 consumed $gVSS^{-1}$ hr^{-1} 3	6	12	30
A	-0.67	0.03	0.12	0.30
B	-0.39	0.34	-0.02	0.31
C	0.23	0.47	0.50	0.38
Average	-0.274	0.279	0.200	0.330
sum $(\sigma_1^2/n_1 + \sigma_2^2/n_2)$	0.0430	0.0216	0.0452	0.0422
Stdev	0.207	0.147	0.213	0.205

Table C-3: SOUR and nSOUR for day 184 (TCMP used as nitrification inhibitor).

SOUR for trials with ATU (No Nitrification)

Fermenter supernatant dilution (1:x)	mg O_2 consumed $gVSS^{-1}$ hr^{-1}		
	1	6	30
A	11.52	11.59	9.59
B	11.21	11.17	9.87
C		10.53	9.97
Average	11.365	11.094	9.810
Stdev	0.2216	0.5324	0.1978

SOUR for trials without TCMP (Nitrification)

Fermenter supernatant dilution (1:x)	mg O_2 consumed $gVSS^{-1}$ hr^{-1}		
	1	6	30
A	10.97	13.88	10.28
B	10.66	13.00	10.76
C		12.01	10.64
Average	10.815	12.960	10.557
Stdev	0.2145	0.9339	0.2510

SOUR accounting for Nitrification (SOUR Difference) - nSOUR

Fermenter supernatant dilution (1:x)	mg O_2 consumed $gVSS^{-1}$ hr^{-1}		
	1	6	30
A	-0.56	2.29	0.69
B	-0.55	1.83	0.89
C		1.48	0.66
Average	-0.550	1.866	0.747
sum $(\sigma_1^2/n_1 + \sigma_2^2/n_2)$	0.0317	0.3852	0.0340
Stdev (sqrt)	0.178	0.621	0.185

C.2 NITRITE GENERATION RATE INHIBITION EXPERIMENTS

C.2.1 Sodium Azide (NaN_3) concentration optimization

Table C-4 NO_2^- and NGR results for each NaN_3 concentration.

NaN_3 = 0 μM NGR (mg/L N min^{-1}): 0.0108

Time	NO_2^- (mg/L-N)[1]									
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	2.8	2.7	2.8	2.7	2.6	2.6	2.7	2.7	2.7	0.1
15	3.2	3.4	3.3	3.2	3.2	3.3	3.4	3.5	3.3	0.1
30	2.8	3.3	3.3	3.3	4.1	3.9	3.9	4.2	3.6	0.5
45	2.6	3.0	2.9	3.0	3.8	3.9	3.7	3.7	3.3	0.5
60	3.3	3.4	3.5	3.4	3.6	3.4	3.6	3.7	3.5	0.1

NaN_3 = 50 μM NGR (mg/L N min^{-1}): 0.0274

Time	NO_2^- (mg/L-N)									
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	3.1	3.3	3.4	3.4	3.2	3.1	3.2	3.2	3.2	0.1
15	3.5	4.0	3.6	3.9	N/A	3.4	3.6	3.1	3.6	0.3
30	4.0	3.9	3.8	3.8	3.2	3.2	3.1	3.3	3.5	0.4
45	4.1	4.2	4.0	4.1	4.6	4.5	4.4	4.8	4.3	0.3
60	4.9	4.7	4.8	4.9	5.0	4.8	5.0	5.1	4.9	0.1

NaN_3 = 100 μM NGR (mg/L N min^{-1}): 0.0485

Time	NO_2^- (mg/L-N)									
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	2.4	2.4	2.3	2.4	2.4	2.2	2.5	2.4	2.4	0.1
15	3.0	3.2	3.3	3.3	3.0	3.0	N/A	3.6	3.2	0.2
30	4.1	4.1	3.9	3.9	3.6	3.5	3.6	3.6	3.8	0.3
45	4.7	4.9	4.7	5.0	4.7	4.9	4.8	5.3	4.9	0.2
60	5.1	5.1	4.9	5.1	5.3	5.4	5.5	5.2	5.2	0.2

NaN_3 = 150 μM NGR (mg/L N min^{-1}): 0.0426

Time	NO_2^- (mg/L-N)									
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	2.7	2.6	2.8	2.8	3.2	3.0	3.0	3.0	2.9	0.2
15	3.2	N/A	3.7	3.4	2.8	2.9	2.6	2.7	3.1	0.4
30	3.7	3.7	4.1	4.1	4.2	4.2	4.2	4.2	4.0	0.2
45	4.5	4.7	4.9	4.6	4.7	4.7	4.6	4.7	4.7	0.1
60	5.4	5.3	5.1	5.4	N/A	N/A	N/A	N/A	5.3	0.1

NaN_3 = 200 μM NGR (mg/L N min^{-1}): 0.0437

Time	NO_2^- (mg/L-N)									
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	2.8	2.7	2.6	2.8	3.0	3.1	3.1	3.2	2.9	0.2
15	3.2	3.5	3.5	3.1	2.8	3.0	3.1	2.6	3.1	0.3
30	4.3	4.3	4.3	4.2	4.1	4.1	4.3	4.2	4.2	0.1
45	4.5	4.7	4.9	4.9	4.9	4.7	4.8	4.8	4.8	0.2
60	5.4	5.4	5.4	5.4	5.3	5.3	5.3	5.4	5.4	0.0

NaN_3 = 250 μM NGR (mg/L N min^{-1}): 0.0411

Time	NO_2^- (mg/L-N)									
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	3.0	3.0	2.7	2.8	2.9	3.0	2.9	2.9	2.9	0.1
15	3.1	3.2	N/A	2.8	3.1	2.9	3.1	-1.0	2.5	1.5
30	3.3	3.5	3.5	3.5	3.2	3.3	3.3	3.3	3.3	0.1
45	3.8	3.8	3.9	3.8	4.6	4.7	4.7	4.7	4.2	0.5
60	5.1	5.3	N/A	N/A	5.0	5.0	N/A	N/A	5.1	0.2

NaN_3 = 300 μM NGR (mg/L N min^{-1}): 0.0385

Time	NO_2^- (mg/L-N)									
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	2.0	3.0	2.5	2.9	2.6	2.4	2.5	2.6	2.6	0.3
15	2.9	2.8	3.4	3.6	2.5	3.0	2.3	2.4	2.9	0.5
30	4.0	4.1	4.1	3.9	4.0	3.9	3.9	4.0	4.0	0.1
45	4.0	4.0	4.1	4.1	4.3	4.1	4.2	4.3	4.1	0.1
60	4.8	4.8	4.8	4.9	N/A	N/A	N/A	N/A	4.8	0.0

[1]Rep 1-4 are from biological duplicate number 1, and Rep 5-8 are from biological duplicate number 2.

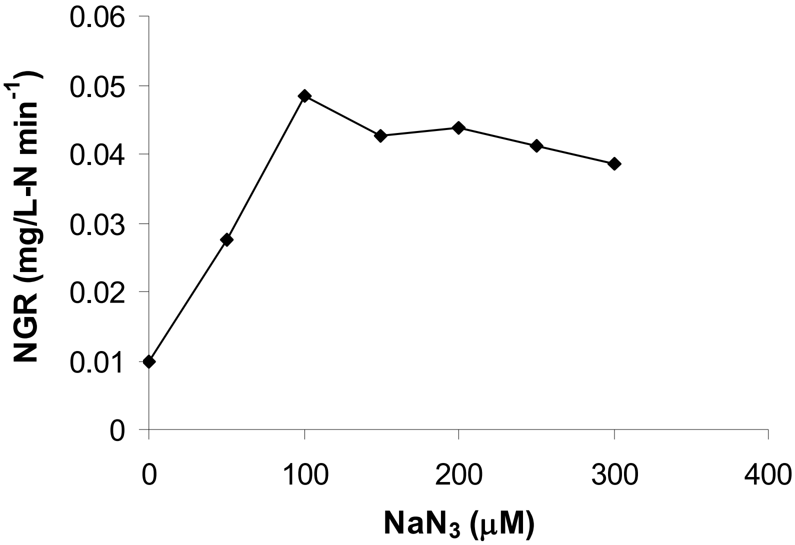

Figure C-2: A NaN_3 optimum concentration of 200 μM was chosen.

C.2.2 Nitrite generation rate experiments data using 200 μM NaN_3 to inhibit NOB.

Table C-5: VSS concentration for NGR experiments.

Date	Day	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)
8/4/2007	339	5020	4800	4960	4927	114

Table C-6: NO_2^- and NGR results from experiments performed on day 339 with concentrated fermenter effluent supernatant.

	NO_2^- (mg/L-N)[1]									
Time	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	0.04	0.04	0.03	0.05	0.04	0.04	0.06	0.01	0.04	0.01
15	0.03	0.03	0.02	0.01	0.02	0.02	0.03	0.06	0.03	0.02
30	0.05	0.07	0.05	0.04	0.05	0.10	0.06	0.02	0.06	0.02
45	0.09	0.01	0.02	0.02	0.01	0.07	0.07	0.00	0.04	0.03
60	0.00	0.10	0.01	-0.02	0.01	-0.02	0.00	0.00	0.01	0.04
NGR (mg/L N min^{-1})	0.000	0.0007	0.000	-0.001	-0.001	0.000	-0.001	-0.001		
Average (mgN $gVSS^{-1}$ day^{-1})				-0.143						
Standard deviation (mgN $gVSS^{-1}$ day^{-1})				0.062						

[1]Rep 1-4 are from biological duplicate number 1, and Rep 5-8 are from biological duplicate number 2.

Table C-7: NO_2^- and NGR results from experiments performed on day 339 with fermenter effluent supernatant dilution of 1:2 (1 part fermenter supernatant: 2 total parts).

	NO_2^- (mg/L-N)[1]									
Time	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	-0.04	-0.03	-0.03	-0.02	-0.03	-0.02	-0.01	-0.03	-0.03	0.01
15	0.02	0.02	0.02	0.02	0.06	0.06	0.07	0.06	0.04	0.02
30	0.02	0.00	0.00	0.01	0.06	0.06	0.07	0.06	0.04	0.03
45	0.03	0.02	0.02	0.02	0.27	0.26	0.25	0.24	0.14	0.12
60	0.24	0.24	0.23	0.24	0.51	0.52	0.52	0.51	0.37	0.15
NGR (mg/L N min^{-1})	0.004	0.004	0.003	0.004	0.009	0.009	0.008	0.008		

Average (mgN $gVSS^{-1}$ day^{-1})	1.714
Standard deviation (mgN $gVSS^{-1}$ day^{-1})	0.754

[1]Rep 1-4 are from biological duplicate number 1, and Rep 5-8 are from biological duplicate number 2.

Table C-8: NO_2^- and NGR results from experiments performed on day 339 with fermenter effluent supernatant dilution of 1:5.

Time	NO_2^- (mg/L-N)[1]									
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	-0.11	-0.06	-0.10	-0.09	-0.10	-0.10	-0.06	-0.07	-0.09	0.02
15	0.12	0.11	0.12	0.12	0.15	0.14	0.15	0.15	0.13	0.02
30	0.32	0.35	0.34	0.33	0.35	0.34	0.35	0.34	0.34	0.01
45	0.62	0.64	0.61	0.61	0.68	0.70	0.67	0.67	0.65	0.03
60	0.88	0.88	0.88	0.89	0.91	0.89	0.91	0.93	0.90	0.02
NGR (mg/L N min^{-1})	0.017	0.016	0.016	0.016	0.017	0.017	0.016	0.017		
Average (mgN $gVSS^{-1}$ day^{-1})				4.742						
Standard deviation (mgN $gVSS^{-1}$ day^{-1})				0.098						

[1]Rep 1-4 are from biological duplicate number 1, and Rep 5-8 are from biological duplicate number 2.

Table C-9: NO_2^- and NGR results from experiments performed on day 339 with fermenter effluent supernatant dilution of 1:10.

Time	NO_2^- (mg/L-N)[1]									
	Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	-0.03	-0.05	-0.04	-0.03	-0.05	-0.03	-0.03	-0.03	-0.04	0.01
15	0.19	0.27	0.17	0.17	0.17	0.16	0.14	0.15	0.18	0.04
30	0.35	0.34	0.38	0.38	0.34	0.33	0.34	0.32	0.35	0.02
45	0.58	0.56	0.54	0.56	0.55	0.58	0.56	0.57	0.56	0.01
60	0.80	0.77	0.77	0.79	0.90	0.88	0.94	0.93	0.85	0.07
NGR (mg/L N min^{-1})	0.014	0.013	0.013	0.014	0.015	0.015	0.016	0.016		
Average (mgN $gVSS^{-1}$ day^{-1})				4.115						
Standard deviation (mgN $gVSS^{-1}$ day^{-1})				0.336						

[1]Rep 1-4 are from biological duplicate number 1, and Rep 5-8 are from biological duplicate number 2.

Table C-10: NO_2^- and NGR results from experiments performed on day 339 with no fermenter effluent supernatant.

Time	NO_2^- (mg/L-N)[1] Rep 1	Rep 2	Rep 3	Rep 4	Rep 5	Rep 6	Rep 7	Rep 8	Average	Standard deviation
0	0.01	0.01	0.01	0.10	0.03	-0.06	-0.06	-0.04	0.00	0.05
15	0.37	0.37	0.30	0.33	0.23	0.20	0.20	0.22	0.28	0.07
30	0.70	0.71	0.77	0.73	0.56	0.57	0.52	0.50	0.63	0.11
45	1.09	1.08	1.25	1.25	0.75	0.69	0.70	0.70	0.94	0.26
60	1.56	1.58	1.72	1.75	0.96	1.03	0.88	0.81	1.29	0.40
NGR (mg/L N min^{-1})	0.026	0.026	0.029	0.028	0.016	0.018	0.016	0.015		
Average (mgN $gVSS^{-1}$ day^{-1})				6.180						
Standard deviation (mgN $gVSS^{-1}$ day^{-1})				1.753						

[1]Rep 1-4 are from biological duplicate number 1, and Rep 5-8 are from biological duplicate number 2.

C.3 BIOWIN® SENSITIVITY ANALYSIS. MODEL CONFIGURED ACCORDING TO SECTION A.1

Each kinetic and stoichiometric parameter listed in Table 4-2 for both AOB and NOB was tested at -50, -30, -10, 10, 30, and 50 percent of the default values. The TAN, NO_2^- and NO_3^- present at the end of the aerobic phase was recorded (Section C.3.1).

C.3.1 AOB parameters for baseline 1 (DO = 0.8 mg/L)

Table C-11: Responses to changes in AOB Yield.

Percent Change	-50	-30	-10	0	10	30	50
Yield (mg COD / mg N)	0.075	0.105	0.135	0.15	0.165	0.195	0.225
TAN at the end of the aerobic phase	0.22	0.23	0.24	0.24	0.24	0.25	0.25
NO_2^--N at the end of the aerobic phase	0.05	0.05	0.05	0.05	0.05	0.04	0.04
NO_3^--N at the end of the aerobic phase	2.40	2.40	2.41	2.41	2.40	2.40	2.40
Relative Sensitivity - TAN	0.2	0.1	0.1	0.0	0.1	0.1	0.1
Relative Sensitivity - NO_2^--N	-0.1	0.0	0.0	0.0	0.0	0.0	0.0
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table C-12: Response to changes in AOB half saturation coefficient.

Percent Change	-50	-30	-10	0	10	30	50
Substrate [NH_4^+] half saturation coefficient (mgN/L)	0.35	0.49	0.63	0.7	0.77	0.91	1.05
TAN at the end of the aerobic phase	0.14	0.18	0.22	0.24	0.26	0.30	0.33
NO_2^--N at the end of the aerobic phase	0.05	0.05	0.05	0.05	0.04	0.04	0.04

NO_3^--N at the end of the aerobic phase	2.38	2.39	2.40	2.40	2.41	2.42	2.43
Relative Sensitivity - TAN	0.9	0.8	0.8		0.8	0.7	0.7
Relative Sensitivity - NO_2^--N	-0.4	-0.3	-0.3		-0.3	-0.3	-0.2
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-13: Response to changes in AOB aerobic decay rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Aerobic decay rate (day^{-1})	0.085	0.119	0.153	0.17	0.187	0.221	0.255
TAN at the end of the aerobic phase	0.18	0.21	0.23	0.24	0.26	0.28	0.30
NO_2^--N at the end of the aerobic phase	0.05	0.05	0.05	0.05	0.04	0.04	0.04
NO_3^--N at the end of the aerobic phase	2.34	2.36	2.39	2.40	2.42	2.45	2.48
Relative Sensitivity - TAN	0.5	0.5	0.5		0.5	0.5	0.5
Relative Sensitivity - NO_2^--N	-0.2	-0.2	-0.2		-0.2	-0.2	-0.2
Relative Sensitivity - NO_3^--N	0.1	0.1	0.1		0.1	0.1	0.1

Table C-14: Response to changes in AOB anoxic/anaerobic decay rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Anoxic/Anaerobic decay rate (day^{-1})	0.04	0.056	0.072	0.08	0.088	0.104	0.12
TAN at the end of the aerobic phase	0.21	0.22	0.24	0.24	0.25	0.26	0.27
NO_2^--N at the end of the aerobic phase	0.05	0.05	0.05	0.05	0.04	0.04	0.04
NO_3^--N at the end of the aerobic phase	2.37	2.38	2.40	2.40	2.41	2.43	2.44
Relative Sensitivity - TAN	0.2	0.2	0.2		0.2	0.2	0.2
Relative Sensitivity - NO_2^--N	-0.1	-0.1	-0.1		-0.1	-0.1	-0.1
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-15: Response to changes in AOB nitrous acid inhibition coefficient, $KiHNO_2$ (mmol/L).

Percent Change	-50	-30	-10	0	10	30	50
$KiHNO_2$ (mmol/L)	0.0025	0.0035	0.0045	0.005	0.0055	0.0065	0.0075
TAN at the end of the aerobic phase	0.24	0.24	0.24	0.24	0.24	0.24	0.24
NO_2^--N at the end of the aerobic phase	0.05	0.05	0.05	0.05	0.05	0.05	0.05
NO_3^--N at the end of the aerobic phase	2.40	2.40	2.40	2.40	2.40	2.40	2.40
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-16: Response to changes in AOB maximum specific growth rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Max specific growth rate (day^{-1}), μ_m	0.45	0.63	0.81	0.9	0.99	1.17	1.35
TAN at the end of the aerobic phase	3.12	0.41	0.28	0.24	0.21	0.17	0.14
NO_2^--N at the end of the aerobic phase	0.09	0.04	0.04	0.05	0.05	0.05	0.05
NO_3^--N at the end of the aerobic phase	2.51	2.58	2.45	2.40	2.37	2.33	2.31
Relative Sensitivity - TAN	-23.7	-2.2	-1.5		-1.2	-1.0	-0.8
Relative Sensitivity - NO_2^--N	-2.2	0.3	0.6		0.5	0.5	0.4
Relative Sensitivity - NO_3^--N	-0.1	-0.2	-0.2		-0.1	-0.1	-0.1

C.3.2 AOB parameters for baseline 2 (DO = 2.0 mg/L)

Table C-17: Response to changes in AOB Yield.

Percent Change	-50	-30	-10	0	10	30	50
Yield (mg COD / mg N)	0.075	0.105	0.135	0.15	0.165	0.195	0.225
TAN at the end of the aerobic phase	0.20	0.21	0.21	0.21	0.22	0.22	0.22
NO_2^--N at the end of the aerobic phase	0.03	0.03	0.03	0.03	0.03	0.03	0.03
NO_3^--N at the end of the aerobic phase	3.29	3.29	3.28	3.28	3.28	3.27	3.27
Relative Sensitivity - TAN	0.2	0.1	0.1		0.1	0.1	0.1
Relative Sensitivity - NO_2^--N	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-18: Response to changes in AOB half saturation coefficient.

Percent Change	-50	-30	-10	0	10	30	50
Substrate [NH_4^+] half saturation coefficient (mgN/L)	0.35	0.49	0.63	0.7	0.77	0.91	1.05
TAN at the end of the aerobic phase	0.12	0.16	0.20	0.21	0.23	0.27	0.30
NO_2^--N at the end of the aerobic phase	0.03	0.03	0.03	0.03	0.03	0.03	0.02
NO_3^--N at the end of the aerobic phase	3.28	3.28	3.28	3.28	3.28	3.28	3.28
Relative Sensitivity - TAN	0.9	0.9	0.9		0.8	0.8	0.8
Relative Sensitivity - NO_2^--N	-0.3	-0.3	-0.2		-0.2	-0.2	-0.2
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-19: Response to changes in AOB aerobic decay rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Aerobic decay rate (day^{-1})	0.085	0.119	0.153	0.17	0.187	0.221	0.255
TAN at the end of the aerobic phase	0.15	0.18	0.20	0.21	0.23	0.26	0.28
NO_2^--N at the end of the aerobic phase	0.03	0.03	0.03	0.03	0.03	0.03	0.03
NO_3^--N at the end of the aerobic phase	3.26	3.27	3.27	3.28	3.28	3.30	3.31
Relative Sensitivity - TAN	0.6	0.6	0.6		0.6	0.6	0.6
Relative Sensitivity - NO_2^--N	-0.2	-0.2	-0.2		-0.1	-0.1	-0.1
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-20: Response to changes in AOB anoxic/anaerobic decay rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Anoxic/Anaerobic decay rate (day^{-1})	0.04	0.056	0.072	0.08	0.088	0.104	0.12
TAN at the end of the aerobic phase	0.19	0.20	0.21	0.21	0.22	0.23	0.24
NO_2^--N at the end of the aerobic phase	0.03	0.03	0.03	0.03	0.03	0.03	0.03
NO_3^--N at the end of the aerobic phase	3.27	3.27	3.28	3.28	3.28	3.28	3.29
Relative Sensitivity - TAN	0.2	0.2	0.2		0.2	0.2	0.2
Relative Sensitivity - NO_2^--N	-0.1	-0.1	-0.1		0.0	0.0	0.0
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-21: Response to changes in AOB nitrous acid inhibition coefficient, $KiHNO_2$ (mmol/L).

Percent Change	-50	-30	-10	0	10	30	50
$KiHNO_2$ (mmol/L)	0.0025	0.0035	0.0045	0.005	0.0055	0.0065	0.0075
TAN at the end of the aerobic phase	0.21	0.21	0.21	0.21	0.21	0.21	0.21
NO_2^--N at the end of the aerobic phase	0.03	0.03	0.03	0.03	0.03	0.03	0.03
NO_3^--N at the end of the aerobic phase	3.28	3.28	3.28	3.28	3.28	3.28	3.28
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-22: Response to changes in AOB maximum specific growth rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Max specific growth rate (day^{-1}), μ_m	0.45	0.63	0.81	0.9	0.99	1.17	1.35
TAN at the end of the aerobic phase	1.16	0.34	0.25	0.21	0.19	0.15	0.12
NO_2^--N at the end of the aerobic phase	0.04	0.02	0.03	0.03	0.03	0.03	0.03
NO_3^--N at the end of the aerobic phase	3.33	3.35	3.29	3.28	3.27	3.26	3.26
Relative Sensitivity - TAN	-8.8	-2.0	-1.6		-1.3	-1.0	-0.8
Relative Sensitivity - NO_2^--N	-0.9	0.3	0.3		0.3	0.3	0.3
Relative Sensitivity - NO_3^--N	0.0	-0.1	0.0		0.0	0.0	0.0

C.3.3 NOB maximum sensitivities

Table C-23: Response to changes in key kinetic and stoichiometric parameters for NOB.

				Percent Change			
Biowin Parameter	-50	-30	-10	(default)	10	30	50
Yield (mg COD / mg N)	0.045	0.063	0.081	0.09	0.099	0.117	0.135
Substrate (NO_2^-) half saturation. (mgN/L)	0.025	0.035	0.045	0.05	0.055	0.065	0.075
Aerobic decay rate (1/d)	0.085	0.119	0.153	0.17	0.187	0.221	0.255
Anoxic/Anaerobic decay rate (1/d)	0.04	0.056	0.072	0.08	0.088	0.104	0.12
$KiHNH_3$ (mmol/L)	0.0375	0.0525	0.0675	0.075	0.0825	0.0975	0.1125
Maximum specific growth rate (1/d)	0.35	0.49	0.63	0.7	0.77	0.91	1.05

Table C-24: NOB Maximum Sensitivity.

Biowin Parameter	BL_1[a] (DO = 0.8 mg/L) NO_2^-	NO_3^-	BL_2 (DO = 2.0 mg/L) NO_2^-	NO_3^-
Yield (mg COD / mg N)	0.4	0.1	0.3	0.0
Substrate [NO_2^-] half saturation. (mgN/L)	1.0	0.1	1.0	0.0
Aerobic decay rate (1/d)	1.0	0.2	0.9	0.1
Anoxic/Anaerobic decay rate (1/d)	0.7	0.1	0.4	0.0
$KiHNH_3$ (mmol/L)	0.029	0.010	0.018	0.003
Max specific growth rate (1/d)	53.1	1.4	87.8	0.9

[a]BL = base line

C.3.4 NOB parameters for baseline 1 (DO = 0.8 mg/L)

Table C-25: Response to changes in NOB yield.

Percent Change	-50	-30	-10	0	10	30	50
Yield (mg COD / mg N)	0.045	0.063	0.081	0.09	0.099	0.117	0.135
TAN at the end of the aerobic phase	0.24	0.24	0.24	0.24	0.24	0.24	0.24
NO_2^--N at the end of the aerobic phase	0.04	0.04	0.04	0.05	0.05	0.05	0.05
NO_3^--N at the end of the aerobic phase	2.54	2.47	2.42	2.41	2.39	2.37	2.35
Relative Sensitivity - TAN	-0.002	-0.002	-0.001		-0.001	-0.001	-0.001
Relative Sensitivity - NO_2^--N	0.4	0.4	0.3		0.3	0.3	0.2
Relative Sensitivity - NO_3^--N	-0.1	-0.1	-0.1		-0.1	-0.1	0.0

Table C-26: Response to changes in NOB half saturation coefficient (NO_2^-).

Percent Change	-50	-30	-10	0	10	30	50
Substrate (NO_2^-) half saturation coefficient (mgN/L)	0.025	0.035	0.045	0.05	0.055	0.065	0.075
TAN at the end of the aerobic phase	0.24	0.24	0.24	0.24	0.24	0.24	0.24
NO_2^--N at the end of the aerobic phase	0.02	0.03	0.04	0.05	0.05	0.06	0.07
NO_3^--N at the end of the aerobic phase	2.56	2.49	2.43	2.41	2.38	2.34	2.29
Relative Sensitivity - TAN	0.01	0.01	0.01		0.01	0.01	0.01
Relative Sensitivity - NO_2^--N	0.99	0.99	0.98		0.97	0.96	0.96
Relative Sensitivity - NO_3^--N	-0.13	-0.12	-0.11		-0.10	-0.10	-0.09

Table C-27: Response to changes in NOB Aerobic decay rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Aerobic decay rate (day^{-1})	0.085	0.119	0.153	0.17	0.187	0.221	0.255
TAN at the end of the aerobic phase	0.24	0.24	0.24	0.24	0.24	0.24	0.24
NO_2^--N at the end of the aerobic phase	0.03	0.04	0.04	0.05	0.05	0.06	0.07
NO_3^--N at the end of the aerobic phase	2.61	2.52	2.44	2.41	2.37	2.29	2.22
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	0.7	0.7	0.8		0.9	0.9	1.0
Relative Sensitivity - NO_3^--N	-0.2	-0.2	-0.2		-0.2	-0.2	-0.2

Table C-28: Response to changes in NOB anoxic/anaerobic decay rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Anoxic/Anaerobic decay rate (day^{-1})	0.04	0.056	0.072	0.08	0.088	0.104	0.12
TAN at the end of the aerobic phase	0.24	0.24	0.24	0.24	0.24	0.24	0.24
NO_2^--N at the end of the aerobic phase	0.03	0.04	0.04	0.05	0.05	0.05	0.06
NO_3^--N at the end of the aerobic phase	2.55	2.49	2.43	2.41	2.38	2.33	2.27
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	0.5	0.5	0.6		0.6	0.6	0.7
Relative Sensitivity - NO_3^--N	-0.1	-0.1	-0.1		-0.1	-0.1	-0.1

Table C-29: Response to changes in NOB $KiHNH_3$ coefficient (mmol/L).

Percent Change	-50	-30	-10	0	10	30	50
$KiHNH_3$ (mmol/L)	0.0375	0.0525	0.0675	0.075	0.0825	0.0975	0.1125
TAN at the end of the aerobic phase	0.24	0.24	0.24	0.24	0.24	0.24	0.24
NO_2^--N at the end of the aerobic phase	0.05	0.05	0.05	0.05	0.05	0.05	0.04
NO_3^--N at the end of the aerobic phase	2.39	2.40	2.40	2.41	2.41	2.41	2.41
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-30: Response to changes in NOB maximum specific growth rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Maximum specific growth rate (day^{-1}), μ_m	0.35	0.49	0.63	0.7	0.77	0.91	1.05
TAN at the end of the aerobic phase	0.25	0.25	0.24	0.24	0.24	0.24	0.24
NO_2^--N at the end of the aerobic phase	1.25	0.17	0.06	0.05	0.04	0.03	0.02
NO_3^--N at the end of the aerobic phase	0.70	1.89	2.28	2.41	2.52	2.72	2.89
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	-53.1	-9.4	-3.2		-2.1	-1.5	-1.1
Relative Sensitivity - NO_3^--N	1.4	0.7	0.5		0.5	0.4	0.4

C.3.5 NOB parameters for baseline 2 (DO = 2.0 mg/L)

Table C-31: Response to changes in NOB yield.

Percent Change	-50	-30	-10	0	10	30	50
Yield (mg COD / mg N)	0.045	0.063	0.081	0.09	0.099	0.117	0.135
TAN at the end of the aerobic phase	0.21	0.21	0.21	0.21	0.21	0.21	0.21
NO_2^--N at the end of the aerobic phase	0.02	0.02	0.03	0.03	0.03	0.03	0.03
NO_3^--N at the end of the aerobic phase	3.34	3.31	3.29	3.28	3.27	3.26	3.25
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	0.3	0.3	0.2		0.2	0.2	0.2
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-32: Response to changes in NOB half saturation coefficient (NO_2^-).

Percent Change	-50	-30	-10	0	10	30	50
Substrate (NO_2^-) half saturation coefficient (mgN/L)	0.025	0.035	0.045	0.05	0.055	0.065	0.075
TAN at the end of the aerobic phase	0.21	0.21	0.21	0.21	0.21	0.22	0.22
NO_2^--N at the end of the aerobic phase	0.01	0.02	0.02	0.03	0.03	0.03	0.04
NO_3^--N at the end of the aerobic phase	3.34	3.31	3.29	3.28	3.27	3.25	3.23
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	1.0	1.0	1.0		1.0	1.0	1.0
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-33: Response to changes in NOB Aerobic decay rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Aerobic decay rate (day^{-1})	0.085	0.119	0.153	0.17	0.187	0.221	0.255
TAN at the end of the aerobic phase	0.21	0.21	0.21	0.21	0.21	0.21	0.21
NO_2^--N at the end of the aerobic phase	0.02	0.02	0.02	0.03	0.03	0.03	0.04
NO_3^--N at the end of the aerobic phase	3.39	3.34	3.30	3.28	3.26	3.23	3.19
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	0.6	0.7	0.8		0.8	0.9	0.9
Relative Sensitivity - NO_3^--N	-0.1	-0.1	-0.1		-0.1	-0.1	-0.1

Table C-34: Response to changes in NOB anoxic/anaerobic decay rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Anoxic/Anaerobic decay rate (day^{-1})	0.04	0.056	0.072	0.08	0.088	0.104	0.12
TAN at the end of the aerobic phase	0.21	0.21	0.21	0.21	0.21	0.21	0.21
NO_2^--N at the end of the aerobic phase	0.02	0.02	0.03	0.03	0.03	0.03	0.03
NO_3^--N at the end of the aerobic phase	3.32	3.30	3.29	3.28	3.27	3.25	3.24
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	0.3	0.3	0.3		0.3	0.4	0.4
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-35: Response to changes in NOB $KiHNH_3$ coefficient (mmol/L).

Percent Change	-50	-30	-10	0	10	30	50
$KiHNH_3$ (mmol/L)	0.0375	0.0525	0.0675	0.075	0.0825	0.0975	0.1125
TAN at the end of the aerobic phase	0.21	0.21	0.21	0.21	0.21	0.21	0.21
NO_2^--N at the end of the aerobic phase	0.03	0.03	0.03	0.03	0.03	0.03	0.03
NO_3^--N at the end of the aerobic phase	3.27	3.28	3.28	3.28	3.28	3.28	3.28
Relative Sensitivity - TAN	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	0.0	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_3^--N	0.0	0.0	0.0		0.0	0.0	0.0

Table C-36: Response to changes in NOB maximum specific growth rate (day^{-1}).

Percent Change	-50	-30	-10	0	10	30	50
Maximum specific growth rate (day^{-1}), μ_m	0.35	0.49	0.63	0.7	0.77	0.91	1.05
TAN at the end of the aerobic phase	0.22	0.21	0.21	0.21	0.21	0.21	0.21
NO_2^--N at the end of the aerobic phase	1.19	0.06	0.03	0.03	0.02	0.02	0.01
NO_3^--N at the end of the aerobic phase	1.83	3.09	3.23	3.28	3.33	3.41	3.48
Relative Sensitivity - TAN	-0.1	0.0	0.0		0.0	0.0	0.0
Relative Sensitivity - NO_2^--N	-87.8	-4.1	-2.4		-1.7	-1.2	-1.0
Relative Sensitivity - NO_3^--N	0.9	0.2	0.2		0.1	0.1	0.1

C.4 BIOWIN® INHIBITION MODELING

Competitive inhibition was modeled by replacing the half saturation coefficient of AOB, $K_{NH_4^+}$ with the term, $K_{NH_4^+,I}$ (Equation 4-2), in Equation 4-1 where S_I was set to a unit concentration of 1 mg/L and included as the term "user defined 1 (UD1)". K_I was termed K_{NH3I} in the BioWin® simulations and was varied until the TAN removal rate date closely resembled the field data collected from the pilot scale N removal reactor. Similarly, non-competitive inhibition was modeled by replacing the maximum specific growth rate, μ_m, with the term $\hat{\mu}_{AOB,I}$ as defined by Equation 4-4. S_I was again set to a unit concentration of 1 mg/L and included as the term "user defined 1 (UD1)". K_I was termed K_{AOBI} to represent the non-competitive inhibition constant in the modeling simulations.

Table C-37: Field TAN data used to compare inhibition models.

	DO		
	0.90	0.8	
Time	Rep 1 TAN (mg/L-N)	Rep 2 TAN (mg/L-N)	Average TAN
10:10 AM	7.16	4.14	5.65
10:25 AM	6.33	3.94	5.13
10:45 AM	6.49	3.52	5.00
11:15 AM	5.54	3.29	4.42
11:45 AM	4.80	2.41	3.61
12:15 PM	4.30	1.59	2.95
12:45 PM	3.30	0.80	2.05
1:15 PM	2.23	0.00	1.11
2:15 PM	0.02	0.00	0.01

Table C-38: VSS values for TAN removal rate comparison.

Date	DO (mg/L)	Rep 1 (mg/L)	Rep 2 (mg/L)	Rep 3 (mg/L)	Average (mg/L)	Standard Deviation (mg/L)
7/28/2007	0.9	12000	10500	11700	11400	794
8/7/2007	0.8	10400	10000	9800	10067	306
			Average		10733	

Table C-39: Comparison of different inhibition mechanism effects on modeled TAN results using default hydrolysis value, and anoxic hydrolysis factor.

	TAN removal rate directly from linear regression	TAN removal rate	Correlation coefficient	Non-competitive coefficient	Competitive coefficient	VSS	Effluent TAN at time 2:09 PM	New μ_{max}	New K_S
	(mg/L TAN day^{-1})	(mg N g VSS^{-1} day^{-1})	R^2	K_{AOBI}	K_{NH3I}	(mg/L)	(mg/L-N)	(day^{-1})	(mg/L-N)
Field data	-34.178	-3.18	0.9874	--		10733	< 0.01	N/A	N/A
Non inhibited	-104.51	-9.74	0.9946	--	--	10733	0.12	0.9[2]	0.7
Competitive	-37.341	-3.48	0.9558	--	0.35	10733	1.21	0.9[2]	2.7
Non-competitive	-36.173	-3.37	0.9695	1.4	--	10733	1.25	0.525	0.7
Un-competitive	-39.248	-3.66	0.977	0.8	0.00203	10733	0.05	0.4	0.001
Mixed	-36.908	-3.44	0.9663	2	3	10733	0.96	0.6	0.93

Table C-40: Comparison of different inhibition mechanism effects on modeled TAN results using a hydrolysis value that was approximately 50% of the default value and an anoxic hydrolysis factor of 0.

	TAN removal rate directly from linear regression	TAN removal rate	Correlation coefficient	Non-competitive coefficient	Competitive coefficient	VSS	Effluent TAN at time 2:09 PM	New mumax	New K_S
	(mg/L TAN day^{-1})	(mg N g VSS^{-1} day^{-1})	R^2	Kaobi	Knh3i	(mg/L)	(mg/L-N)	(day^{-1})	(mg/L-N)
Field data	-34.178	-3.18	0.9874	--	--	10733	< 0.01	N/A	N/A
Non inhibited	-87.559	-8.24	0.9945	--	--	10621	0.06	0.9[2]	0.7
Competitive	-32.938	-3.09	0.9895	--	0.35	10654	0.99	0.9[2]	2.7
Non-competitive	-30.886	-2.91	0.9951	1.4	--	10618	1.04	0.525	0.7
Un-competitive	-33.887	-3.19	0.9976	0.8	0.0007	10634	0.23	0.4	0.001
Mixed	-31.71	-2.98	0.9943	2	3	10654	0.9	0.6	0.93