

# **Transformation of Carbon, Nitrogen and Phosphorus in Deep Row Biosolids Incorporation-Hybrid Poplar Plantation in Coastal Plain Mined Land Reclamation Sites**

Kirill Igorevich Kostyanovskiy

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Gregory K. Evanylo, chair

Marcus M. Alley

Duane F. Berry

W. Lee Daniels

Thomas R. Fox

Chao Shang

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## **ABSTRACT**

Deep row incorporation (DRI) is a biosolids recycling method that is especially appropriate for reclaiming disturbed land because of the extremely high application rates used. Nutrient additions in excess of the vegetation requirements, especially in coarse-textured soils, can potentially impair water quality. Increasing C and N additions with biosolids DRI can also generate emissions of greenhouse gases  $\text{N}_2\text{O}$  and  $\text{CH}_4$  and decrease the value of C sequestration. Objectives of this research were: (i) compare the effects of DRI biosolids type and rate and annual conventional fertilizer application on N and P leaching losses; (ii) determine the effects of aging on the N, C and P dynamics in the DRI biosolids seams; (iii) compare the effects of biosolids type and conventional N fertilization on  $\text{N}_2\text{O}$ ,  $\text{CH}_4$  and  $\text{CO}_2$  emissions; and (iv) compare the effects of DRI biosolids and conventional N fertilization on hybrid poplar biomass dynamics, C, N and P sequestration. The following eight treatments were established to achieve objectives (i) and (iv): 0 (control), 167, 337, 504  $\text{kg N ha}^{-1} \text{ yr}^{-1}$  as conventional fertilizer; 213 and 426  $\text{Mg ha}^{-1}$  anaerobically digested (AD) and 328 and 656  $\text{Mg ha}^{-1}$  lime stabilized (LS) biosolids applied in trenches. The amount of N lost from the DRI biosolids was 261–803  $\text{kg N ha}^{-1}$ , while the fertilizer treatments were not different from 0  $\text{kg N ha}^{-1} \text{ yr}^{-1}$  control. Orthophosphate and TKP leached in negligible amounts. Deep row biosolids incorporation did not pose P leaching risks but did result in high N leaching below the biosolids seams. Aboveground biomass production in the biosolids treatments was not different from the control treatment and ranged from  $2.1 \pm 0.3$  to  $4.0 \pm 0.5 \text{ kg tree}^{-1}$ . The fertilizer treatments produced significantly less biomass than the control and the biosolids treatments. Hybrid poplars sequestered up to  $3.20 \pm 0.54 \text{ Mg C ha}^{-1}$ ,  $71 \pm 12 \text{ kg N ha}^{-1}$ , and  $11.0 \pm 1.8 \text{ kg P ha}^{-1}$ . The planting density capable of the N uptake in order to avoid N leaching was estimated at 3912 to 11363 trees  $\text{ha}^{-1}$ . Our results suggest increased hybrid poplar planting density and decreased application rates of DRI biosolids may decrease the risk of groundwater contamination with N. Three treatments were compared to address objective (ii): 426  $\text{Mg ha}^{-1}$  AD and 656  $\text{Mg ha}^{-1}$  LS biosolids. Organic C losses were 81  $\text{Mg ha}^{-1}$  and 33  $\text{Mg ha}^{-1}$  for LS and AD biosolids, respectively. Total N lost over the course of two years was 15.2  $\text{Mg ha}^{-1}$  and 10.9  $\text{Mg ha}^{-1}$  for LS and AD biosolids, respectively, which was roughly 50% of the N applied. No significant losses of P were detected. Most of the P was Al- and Fe-bound in the AD biosolids and Ca-bound in the LS biosolids. Our results indicated that recommended rates of DRI biosolids in coarse textured soils should be based on crop N requirements and N mineralization considerations, and P mobility from biosolids of the type used should not pose a water quality risk. Four treatments were compared to address objective (iii): 426  $\text{Mg ha}^{-1}$  AD and 656  $\text{Mg ha}^{-1}$  LS biosolids; 0 (control) and 504  $\text{kg N ha}^{-1} \text{ yr}^{-1}$  as conventional fertilizer. Contributions from  $\text{CH}_4$  and  $\text{CO}_2$  emissions to the radiative forcing were very small compared to  $\text{N}_2\text{O}$ . More  $\text{N}_2\text{O}$  was produced in the DRI biosolids treatments than in the conventional fertilizer treatments, and  $\text{N}_2\text{O}$  production was higher in AD than in LS. Expressed as global warming potentials,  $\text{N}_2\text{O}$  emissions from AD ( $101.5 \text{ Mg C ha}^{-1}$ ) were 4.6 times higher than from LS and 14.5–16.1 times higher than from the fertilizer treatments. High  $\text{N}_2\text{O}$  emissions from deep row incorporated biosolids reduce the C sequestration benefits of the DRI method.

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## CHAPTER 1

### BACKGROUND

Biosolids are defined by United States Environmental Protection Agency (USEPA) as any solid, semisolid, or liquid residue generated during the treatment of domestic, businesses and industrial sewage in a treatment works (40 CFR Part 503), which includes solids removed in primary, secondary, or advanced wastewater treatment, and any substance derived from sewer sludge (USEPA, 1993). Biosolids are composed of inorganic constituents, such as macro- and micro-nutrients and non-nutrient trace elements, organic compounds, microorganisms including pathogens and parasitic protozoa (Evanylo, 2003). More than  $7.4 \times 10^6$  Mg of biosolids are generated annually in the US (USEPA, 1999). Amendments to the Clean Water Act (1987) prohibit disposal of biosolids into the ocean and freshwater aquatic systems and requires local governments to treat municipal wastewater. Owing to their nutrients and organic matter content, biosolids are used as a low-grade fertilizer and soil amendment to improve soil chemical and physical properties (Elliott and O'Connor, 2007).

The part 503 Rule establishes the basic management practices for biosolids, which include maximum concentrations and loading rates for heavy metals and treatments for controlling and reducing pathogens, which were intended to be protective of human health and the environment (NRC, 2002). Sewage sludge is treated to produce biosolids by reducing the content of oxygen demanding compounds, odor, undigested solids, and pathogens. The processes employed to improve biosolids handling characteristics and sanitize the solids include thickening, conditioning, dewatering, processes to significantly reduce pathogens (PSRP) such as

aerobic and anaerobic digestion, and processes to further reduce pathogens (PFRP) as alkaline stabilization, composting, and heat drying (USEPA, 1984; Evanylo, 2003).

Treated biosolids make excellent soil amendments and sources of nutrients for plant growth. Agricultural land application is an important method of utilizing biosolids that provides essential plant nutrients, accumulates organic carbon (C), enhances soil productivity, and improves soil properties. The part 503 rule (USEPA, 1993) requires that application of biosolids to agricultural land is based on nitrogen (N) agronomic rate, except for reclamation sites where the application can be higher. Virginia Biosolids Use Regulations (Virginia Department of Health, 1997) contain recommended land application rates for biosolids based on plant available nitrogen (PAN) for agricultural crops.

Biosolids normally contain similar amounts of PAN and phosphorus (P), but crops require 50–80% less P than N, and biosolids application at rates that supply the N needs of the crop can increase the potential for P contamination of surface water where soil P levels are already high (Evanylo, 1999; USDA/USEPA, 1999; Elliott and O'Connor, 2007). To avoid P runoff and leaching, a conservative approach has been implemented, by basing biosolids application rates on plant P, rather than PAN, requirements. However, P-based biosolids applications are uneconomical and unpractical due to the need of additional N fertilization (Chinault and O'Connor, 2008).

Biosolids have been successfully utilized as soil amendments on agricultural land, forests, and reclamation sites (NRC, 2002), but disagreeable odors that emanate during and after land application sometime incur objections from nearby residents. Deep row incorporation (DRI) of biosolids (Sikora et al., 1979; Sikora and Colacicco, 1980; Kays et al., 1997) is a unique alternative land application method that potentially addresses concerns associated with surface

application techniques and may be an effective post mining reclamation practice. The DRI involves placement of biosolids into trenches that are immediately covered with overburden, eliminating odor problems and maintaining biosolids in a stable, anaerobic environment (Kays et al. 1999). Deep row incorporation differs from the conventional tillage techniques because it is a one-time application of biosolids which provides necessary nutrients to sustain growth for up to 6 years when combined with the culture of N demanding hybrid poplar trees (Kays, 2002). The benefits of such short-rotation plantation system include the production of forest products and wildlife habitat and sequestering C in abandoned, organic matter depleted soils resulting from surface mining. The trees can be harvested for wood products or as a source of bioenergy at the completion of the six-year rotation, during which period most of the available nutrients from the biosolids are utilized (Kays et al., 1999; Felix et al., 2008).

There are several potential drawbacks to the application of large amounts of potentially mineralizable N- and P-rich biosolids using the DRI technique, such as N and P leaching into groundwater and emission of highly potent greenhouse gases  $N_2O$  and  $CH_4$  (IPCC, 2007). Therefore, research is needed to better determine potential benefits and assess associated local and global environmental risks from the biosolids DRI technology.

### **OBJECTIVES**

This research was intended to study the environmental effects of DRI biosolids in a coastal plain heavy mineral mining reclamation site during the initial years following application, by monitoring leaching losses of N and P and greenhouse gas emissions, determining the amounts and distributions of C, N, and P in the biosolids seams, estimating C, N, and P mass balance, and evaluating the hybrid poplar growth response.

The specific objectives were to: (i) compare N and P leaching potential among one time applications of lime stabilized and anaerobically digested DRI biosolids and annual conventional fertilizer applications; (ii) determine the effects of the biosolids and conventional N fertilization on  $N_2O$ ,  $CH_4$  and  $CO_2$  emissions; (iii) determine the influence of location in the biosolids seam on  $N_2O$ ,  $CH_4$  and  $CO_2$  emissions; (iv) determine the effects of aging on C, N, and P dynamics in the DRI biosolids seams; (v) determine the biosolids net masses of C, N, and P retained in the seams after two years of entrenchment; (vi) compare the effects of the DRI biosolids and conventional fertilizer on hybrid poplar growth, biomass production, poplar C, N and P sequestration and foliar response; and (vii) estimate the poplar planting density capable of N uptake to prevent N loss into groundwater from the DRI biosolids.

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## CHAPTER 2

### LITERATURE REVIEW

#### Introduction

The practice of biosolids deep row incorporation (DRI) for the production of fast-growing, high N-assimilating perennial species, such as hybrid poplar, offers a potentially environmentally beneficial approach for utilizing large loading rates of biosolids and reclamation of abandoned and active mined lands by increasing organic matter content of the soil and providing plants with a valuable source of macro- and micro-nutrients. The DRI has been permitted on mineland reclamation sites (Kays et al., 1997; Felton et al., 2008) as an exception to Title 40 CFR Part 503 rule (USEPA, 1993), which requires that application of biosolids to agricultural land is based on nitrogen (N) agronomic rate. The underlying assumption for high biosolids application rates on mineland reclamation sites is that nitrate ( $\text{NO}_3\text{-N}$ ) losses to groundwater will have minimal long term negative effects following one-time application and the benefits from the biosolids application would surpass the short-term negative environmental effects (Daniels et al., 2003). The DRI establishes an organic matter and nutrient rich, low density, anoxic system with high water holding capacity within the biosolids seams (Kays et al., 1997). While DRI is a long-lasting source of nutrients, it may present risks, such as decreased groundwater quality, and potential excessive greenhouse gas emissions influencing global climate change.

#### **Biosolids Deep Row Incorporation for Mineland Reclamation**

Surface mining causes disturbance and degradation of soil, generating large volumes of heterogeneous overburden material, which usually possesses poor physical properties, low soil

organic matter content, and low fertility, which limit their quality and functions. Biosolids are an excellent amendment for mined soils, since they increase soil organic carbon, cation exchange capacity, soil nutrient level, and promote ecosystem recovery after mining (Brown et al., 2003; Ussiri and Lal, 2005; Stehouwer et al., 2006). Title 40 CFR Part 503 rule (USEPA, 1993) determines that biosolids applications to agricultural soils should be based on N plant uptake rates (agronomic N rates). Mined land reclamation sites are frequently exempted from the agronomic N rate application requirement under the assumption that nitrate ( $\text{NO}_3\text{-N}$ ) losses to groundwater will have minimal long term negative effects following one-time application (Haering et al., 2000).

Deep row incorporation of biosolids is an alternative to land application technique which was shown to be very effective in short-rotation plantations of woody species (Kays et al., 1999; Felix et al., 2008). Entrenched biosolids are applied at loading rates significantly higher (e.g. >384 Mg/ha) than the N agronomic rates (Sikora et al., 1980; Kays et al., 1999). Due to reduced organic matter decomposition, the DRI technique has been shown to release N to the trees gradually throughout extended periods of time (Kays et al., 1997; Kays et al., 1999; Felton et al., 2008). Losses of nutrients into groundwater at biosolids deep row incorporation sites are highly dependent on such factors as biosolids organic matter decomposition rate, depth to groundwater, and presence of a low-permeability layer beneath the biosolids seams which would restrict leaching before the roots invade the seam and start nutrient uptake (Sikora et al., 1980).

Within the seam, mineralization rate is highly variable depending on its aeration status. The two major processes responsible for decomposition of organics in the soil vadose zone are aerobic and anaerobic decomposition (Evangelou, 1998). Aerobic decomposition occurs in the presence of oxygen when organic matter is converted to carbon dioxide, water and by-products,



such as ammonium ( $\text{NH}_4\text{-N}$ ), nitrate ( $\text{NO}_3\text{-N}$ ), and phosphate ( $\text{PO}_4\text{-P}$ ). Anaerobic decomposition results in low molecular weight organic acids, which may further be converted to methane (Stevenson, 1982; Evangelou, 1998). Aerobic decomposition results in mineralization of organic compounds and release of plant-available nutrients, which are the ultimate reason for biosolids application.

Entrenched biosolids dewater from the top down; therefore, mineralization and nitrification start from the surface and anaerobic processes such as denitrification may be favored at the bottom of the seam (Sikora et al., 1979). Anaerobic conditions favor reduction of electron acceptors such as  $\text{NO}_3^-$ ,  $\text{MnO}_2$ ,  $\text{Fe}(\text{OH})_3$ ,  $\text{SO}_4^{2-}$  and  $\text{CO}_2$  (Ponnamperuma, 1972; Masscheleyn et al., 1990). Eventually, entrenched biosolids are transformed into stable humus-like media having little potential for environmental impairment (Sikora et al., 1982).

### **Transformation of N in Biosolids**

Nitrogen availability is usually the limiting nutrient factor in growth and development of plants, including forest species (Cooke et al., 2005). Once biosolids are land-incorporated, release of N is controlled by mineralization, which involves conversion of organic forms of N (proteins, amino acids, nucleic acids) to  $\text{NH}_4\text{-N}$ . This process is mediated by heterotrophic microorganisms which use organic matter as an energy source for their metabolism (He et al., 2003). Once mineralized, in favorable pH of 4.5-8  $\text{NH}_4\text{-N}$  can be nitrified in a two-step reaction into nitrite ( $\text{NO}_2\text{-N}$ ), which is catalyzed by nitrosomonas bacteria and then into  $\text{NO}_3\text{-N}$  carried out by chemoautotrophic bacteria nitrobacter. Ammonia volatilization occurs at alkaline pH. The  $\text{pK}_a$  of  $\text{NH}_4\text{-N}$  de-protonation is 9.2, thus approximately 50% of  $\text{NH}_4/\text{NH}_3$  is in  $\text{NH}_3$  form at pH 9.2 (Evangelou, 1998). Ammonia volatilization from biosolids has been shown to remove up to

50% of total N from landfill bioreactors (Berge et al., 2005). Ammonium-N is tightly bound to the negative surfaces of clay minerals or organic matter and, therefore, has low leaching potential (Santibanez et al., 2007), which increases in sandy soils with few negative exchange sites.

Mineralization of N in applied biosolids depends on soil temperature, moisture, and soil type (Gilmour and Clark, 1988; Ajwa and Tabatabai, 1994; Gilmour et al., 1996; Gilmour and Skinner, 1999). USEPA (1995) proposed mineralization rates of 10-40% per year for biosolids originating from different treatment processes based on laboratory incubations. However, the study by Gilmour et al. (2003) found that first-year mineralization rates for different biosolids were 34-42% regardless of the biosolids type.

Mineralization liberates large amounts of  $\text{NH}_4\text{-N}$ , which may be transformed into  $\text{NO}_3\text{-N}$  (Kleber et al., 2000) and would eventually be lost with runoff or leached into groundwater if biosolids provide more N than can be taken up by the plants (Evanylo, 1999). Research has shown that application of biosolids at N rates adequate to meet plants' nutrient requirements ( $100\text{-}800 \text{ kg N ha}^{-1}$ ) will not cause groundwater pollution (Koterba et al., 1979; Riekerk, 1981; Brockway and Urie, 1983; Hallett et al., 1999; Kelty et al., 2004). The study by Kelty et al. (2004) showed that application of the pelletized biosolids at the rates equivalent to  $200\text{-}800 \text{ kg N ha}^{-1}$  to red pine plantation resulted in leaching concentrations of  $\text{NO}_3\text{-N}$  below  $10 \text{ mg l}^{-1}$  as detected by suction lysimeters over the course of 2 years. In the same study, the vegetation-free areas resulted in  $10\text{-}35 \text{ mg l}^{-1}$  of  $\text{NO}_3\text{-N}$  in leachate, depending on the N application rate (Kelty et al., 2004). Brockway and Urie (1983) determined that anaerobically digested municipal sludge could be applied to forest soils without exceeding  $10 \text{ mg l}^{-1}$  of  $\text{NO}_3\text{-N}$  in leachate at biosolids total N rates of  $990 \text{ kg ha}^{-1}$  ( $16.5 \text{ dry Mg biosolids ha}^{-1}$ ) for red pine (*Pinus rubra*) and white pine (*Pinus strobus*) and of  $1140 \text{ kg ha}^{-1}$  ( $10 \text{ dry Mg biosolids ha}^{-1}$ ) for aspen (*Populus tremuloides*).

Application of liquid sludge at 200-800 kg N ha<sup>-1</sup> under hardwood forest resulted in 20-90 mg l<sup>-1</sup> NO<sub>3</sub>-N in leachate during the first year (Aschmann et al., 1992), which demonstrated that N leaching can be highly dependent on the biosolids type.

Various studies have established oxygen availability as an important factor in denitrification rate (Sexstone et al., 1988). Moisture content within biosolids directly affects their aerobicity and, thus, potential denitrification. It follows that anaerobic conditions will develop within the nearly water saturated parts of the biosolids seam, where recharging of air with the atmosphere is impeded. It is known that energy required by microorganisms is generated through oxidation-reduction reactions, transferring electrons from the C atoms existing in the organic compounds to oxygen. Under anoxic conditions, facultative anaerobes would obtain their oxygen requirement by denitrification using NO<sub>3</sub>-N as an electron acceptor, whereas carbon acts as an electron donor in the respiratory chain (Sanchez et al., 2000; Jarvis et al., 2001).

Visual observations on the changes of the biosolids in the trenches reported by Sikora et al. (1979) provided speculation on C and N transformations that may accompany the aging process. The organic N in the sewage sludge needs to be mineralized and then nitrified to NO<sub>3</sub>-N in order to generate a non-attenuated anion capable of leaching. A comparison of chloride (Cl) and NO<sub>3</sub>-N concentrations in water samples collected from below the biosolids was utilized to assess the potential for leaching and denitrification. The ratio of NO<sub>3</sub>-N:Cl decreased with depth below the trench, which the researchers interpreted as evidence for a mechanism for the reduction of NO<sub>3</sub>-N (since both NO<sub>3</sub>-N and Cl are expected to move through the soil at generally the same rate). Sikora et al. (1979) deduced that denitrification had occurred because there were no plant roots that could assimilate N at the depths evaluated and microbial immobilization was unlikely to occur in the low organic C-containing subsoil.

Taylor et al. (1978) proposed that the relatively low oxygen and high methane content of the soil atmosphere adjacent to the biosolids would be an ideal environment for denitrification based on their results from a 160-day simulated deep row greenhouse experiment. They determined that some nitrification had occurred 160 days after incorporation based on the concentration of  $\text{NO}_3\text{-N}$  remaining within the biosolids; however, denitrification was also likely in order to account for the low concentrations of  $\text{NO}_3\text{-N}$  in the soil below the biosolids. The researchers measured  $\text{CO}_2$  concentrations in the soil adjacent to the biosolids ranging from 21 to 25% for much of the 160 days. These  $\text{CO}_2$  concentrations are indicative of conditions anoxic enough to depress mineralization and promote denitrification. Keeney et al. (1985) demonstrated that nitrification rate decreased as  $\text{CO}_2$  concentration in soil increased from 0.3 to 100%, and denitrification (as measured by the generation of  $\text{N}_2\text{O}$ ) increased as  $\text{CO}_2$  concentration increased from 0.3 to 2.6 %.

### **Transformation of C in Biosolids**

Decomposition of organic matter completes the atmosphere-soil-atmosphere C cycle by emitting  $\text{CO}_2$  and accumulating a portion of organic C as a stable humus fraction in soil (Ussiri and Lal, 2005). Pattern of biosolids decomposition is related to the initial chemical composition of the material. Temperature, moisture content, organic N content and soil type were shown to determine organic C decomposition kinetics in land-applied biosolids (Gilmour and Clark, 1988; Ajwa and Tabatabai, 1994; Gilmour et al., 1996). Decomposition and N mineralization are interrelated and were shown to be dependent on the protein content in the biosolids (Rowell et al., 2001), which is strongly correlated with labile organic C (Lerch et al., 1992). Lignin to N ratio is positively correlated with decomposition rate (Melillo et al., 1982), and polyphenolic

compounds are negatively correlated with decomposition (Aerts and deCaluwe, 1997). Decomposition was also shown to be dependent on the C to N ratio in the biosolids (Barbarika et al., 1985; Gilmour and Skinner, 1999). Organic C decomposition rate is constant for some biosolids, while other biosolids exhibit a fast decomposition stage followed by slow decomposition (Gilmour, 1997). The two stage process involves labile organic matter in the fast stage and recalcitrant organic matter during the slow decomposition rate (Parnaudeau et al., 2004). Dissolved organic C associated with N (dissolved organic N) can be one of the N and C loss pathways via leaching (Curtin et al., 1998; Lajtha et al., 2005). Van Kessel et al. (2009) showed that dissolved organic C and dissolved organic N are originating from the same organic matter pools.

### **Greenhouse Gas Emissions from the Biosolids Application**

Nitrous oxide ( $\text{N}_2\text{O}$ ), methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ) are greenhouse gases (GHG) important in radiative forcing and contributing to the global warming effect in the atmosphere. The atmospheric lifetimes of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  are 12 and 114 years, and their global warming potentials are 25x and 298x  $\text{CO}_2$ , respectively, during a 100 year time horizon (IPCC, 2007). Carbon dioxide produced as a result of land application of residuals (i.e., biosolids) has no net effect on global warming, because the C was taken from the atmospheric pool of  $\text{CO}_2$  via photosynthesis (Pierzynski and Gehl, 2005).

Anaerobic conditions in soil systems is the major factor in retarding organic matter decomposition rates, which results in decrease of  $\text{CO}_2$  production and increase of  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions. Soil redox potential (Eh) has been shown by Yu and Patrick (2003) to provide a quantitative measure of oxidizing and/or reducing conditions that govern the dynamics of GHG

production. Increase in GHG emissions following application of organic amendments to soils has been shown in previous studies (Christensen, 1983; Barton and Schipper, 2001; Velthof et al., 2002; Jones et al., 2005; Paramasivam et al., 2008). The magnitude of that effect was demonstrated to be larger (Christensen, 1983; Jones et al., 2005) or similar (Tilsner et al., 2003) to such effect from conventional N fertilization. Greenhouse gas fluxes from landfills are several times higher than from organic-amended agricultural soils (Borjesson and Svensson, 1997; Rinne et al., 2005); therefore, landfilling of wastes, such as biosolids, is discouraged in favor of land application (Wang et al., 2008).

When biosolids are deep row incorporated, anoxic conditions within the biosolids seam may result in generation of CH<sub>4</sub>, as occurs in landfills (Borjesson et al., 1998; Lohila et al., 2007; Zhang et al., 2009). However, the cover soil and biosolids can develop a population of methanotrophic bacteria that have been shown to mitigate the CH<sub>4</sub> emissions in landfills (Borjesson et al., 1998; Mandernack et al., 2000; Chanton et al., 2009; Scheutz et al., 2009; Zhang et al., 2009).

Denitrification is widely recognized as a key biogeochemical process, which converts NO<sub>3</sub>-N, the form available to eukaryotes, to N<sub>2</sub> and N<sub>2</sub>O (Ye et al., 1994). Respiratory denitrification is one of the several processes, such as nitrification, dissimilatory NO<sub>3</sub>-N reduction to NH<sub>4</sub>-N, and chemo-denitrification, which generate N<sub>2</sub>O (Tiedje, 1994; Mahne and Tiedje, 1995). Nitrous oxide is mainly produced as a by-product of nitrification and as an intermediate product of denitrification (Knowles, 1982; Wrage et al., 2001; Mathieu et al., 2006), which are likely to simultaneously occur in different parts of the DRI biosolids trench (Sikora et al., 1979). Methanotrophic bacteria can also generate N<sub>2</sub>O via nitrification (Mandernack et al., 2000), as well as supply simple carbon compounds for denitrifying bacteria growth, therefore contributing

to denitrification (Knowles, 2001; Modin et al., 2007). Most of the times though, the total N<sub>2</sub>O emissions are of interest with less concern in mechanisms causing the fluxes (Tiedje, 1994). Globally, soils account for 65% of the total N<sub>2</sub>O emissions (Kroeze et al., 1999). It was previously shown that application of high rates of organic matter can lead to elevated N<sub>2</sub>O emissions which are able to offset 75-310% of C sequestered in soil in terms of radiative forcing (Li et al., 2005); therefore, such biogeochemical interactions should be taken into account to accurately assess the role of agricultural practices in global climate change.

### **Biosolids P Leaching and Binding Potential**

According to USEPA 40 CFR Part 503 rule biosolids have to be applied at agronomic rates, based on crop N requirements (USEPA, 1993). Due to N-based applications, biosolids application rates  $>2\text{Mg ha}^{-1}$  result in oversupply of P for crop nutrient requirements (Chinault and O'Connor, 2008). Therefore, P was brought to the foreground of the biosolids application-related issues (Brandt et al., 2004; Elliott and O'Connor, 2007) due to concerns over water quality in agricultural systems affected by potential P loss (USDA/USEPA, 1999). Most regulations governing biosolids land application don't consider that P solubility can vary widely among biosolids (Chinault and O'Connor, 2008). Biosolids P is not as labile as in fertilizers and manures, and its lability can be greatly influenced by the wastewater treatment process (Maguire et al., 2001). In fact, most of the wastewater treatment processes lead to immobilization of P. Lime stabilization process raises biosolids pH and supplies Ca which binds P in insoluble Ca phosphates, flocculation techniques enrich biosolids with Al and Fe, which lead to P adsorption on sesquioxides surfaces and insolubilization. Phosphorus leaching from the biosolids remains low due to P-binding in inorganic constituents such as Fe, Al and Ca (Maguire et al., 2000;

Maguire et al., 2001; Elliott et al., 2002). One phosphorus leaching study established on two Florida P-depleted sands by Elliott et al. (2002), employing biosolids, chicken manure and TSP and planted to Bahiagrass, resulted in P leaching (as a percentage of the total) of 21% and 3% for TSP and chicken manure, respectively, and <1% for the biosolids. The only exceptions were biosolids originating from biological P removal processes, which leached 2.5-11% of the total applied P. Stehouwer et al. (2006) reported very low total P concentrations in leachate throughout the study period on former coal mine site at the biosolids application rate of 134 Mg ha<sup>-1</sup>, which exceeds plant N requirement threefold. Siddique and Robinson (2004) determined that the rate of P release (as measured by a cation-anion exchange resin) decreased in the order KH<sub>2</sub>PO<sub>4</sub> and cattle slurry > poultry litter > biosolids during a 100 day incubation of sandy loam soils with KH<sub>2</sub>PO<sub>4</sub>, poultry litter, cattle slurry and anaerobically digested sewage sludge (Thames Water Utilities, UK). Low values of P release from the biosolids were attributed to high levels of exchangeable Ca.

Phosphorus exists in soil in organic and inorganic forms. While a large proportion of soil organic P remains uncharacterized, inositol phosphate, phospholipids, nucleic acids and their derivatives, and polyphosphates are identified (Stevenson, 1982; Kuo, 1996). Inorganic P is represented by an array of compounds associated with Fe, Al and Ca present in soil. Individual P compounds applied with biosolids are very difficult to distinguish. Instead, classes of P compounds are defined operationally by the extractants that remove them in a sequential fractionation scheme (Sui et al., 1999). The fractionation scheme by Chang and Jackson (1957), which was intended to separate Fe-P, Al-P, and Ca-P fractions, has undergone multiple modifications to account for different soil specifics. That scheme, however, is primarily designed for acid and neutral soils (Kuo, 1996). Another fractionation scheme, developed by Hedley et al.



(1982), aims to quantify plant-available P ( $\text{H}_2\text{O}$  or  $\text{NaHCO}_3$  extractable), Fe and Al associated P ( $\text{NaOH}$  extractable), Ca associated P ( $\text{HCl}$  extractable), and residual P ( $\text{H}_2\text{SO}_4$ - $\text{H}_2\text{O}_2$  digestible). With slight modifications, the Hedley et al. (1982) procedure was successfully used for P fractionation of soil amended with low rates ( $6.4$  and  $11.5 \text{ Mg ha}^{-1}$ ) of biosolids by Sui et al. (1999). Sui found that most of the Ca bound P present in lime stabilized biosolids is transformed into labile ( $\text{NaHCO}_3$  extractable) P after application to non-calcareous soils. Maguire et al. (2000) developed a soil P fractionation scheme for the biosolids amended soils in Delaware, Maryland, and Virginia, which included the P fractions of soluble P ( $\text{NH}_4\text{Cl}$  extraction), Al-P ( $\text{NH}_4\text{F}$  extraction), Fe-P ( $\text{NaOH}$  extraction), reductant soluble P (sodium citrate- $\text{NaHCO}_3$ -sodium dithionite), and Ca-P ( $\text{H}_2\text{SO}_4$ ). He found that biosolids applications increased Fe-P in soils, and Al-P tended to be higher in biosolids-amended soils than in buffer areas. O'Connor et al. (2004) implemented a P fractionation scheme modified from Chang et al. (1983) to determine the P fractions in the biosolids amended sandy Florida soil and in biosolids. The fractions included soluble/exchangeable P ( $\text{KCl}$  extraction), Fe and Al bound P ( $\text{NaOH}$  extraction), and Ca and Mg bound P ( $\text{HCl}$  extraction). The sum of three extractions was identified as inorganic P in a material, although some organic P can be extracted with  $\text{NaOH}$  (Sui et al., 1999).

### **Poplar Trees as Sinks of Nutrients**

Hybrid poplar (*Populus spp.*) plantations are economically attractive to meet world's increasing demand for forest products (Fox, 2000) due to their high growth rate and biomass production. Poplars are dioecious woody plants commonly found in temperate regions of the world, particularly in riparian zones. Plant breeders developed an array of hybrids on the basis of interspecific crosses of *Populus deltoides*, *Populus maximowiczii*, *Populus trichocarpa*, *Populus*

*nigra* and *Populus balsamifera*, which are considered one of the most productive hardwood species (Braatne, 1999). Poplars are commonly grown as short rotation plantations (Karp, 2008), as they can yield substantially more biomass than native forests, particularly when supplemental fertilizer is applied (McLaughlin et al., 1987). Yields of 18.2 dry Mg ha<sup>-1</sup>yr<sup>-1</sup> have been reported for some poplar clones (DeBell et al., 1996), demonstrating poplar's potential as an important C sink.

Nitrogen is the nutrient most likely to limit growth, and N fertilization is effective in increasing poplar yields (Hansen et al., 1988). Estimated annual N uptake for poplar trees ranges from 95 to 276 kg ha<sup>-1</sup> year<sup>-1</sup> (Heilman and Stettler, 1986), but poplars are capable of assimilating 224 to 404 kg N ha<sup>-1</sup> year<sup>-1</sup> (National, Agroforestry Center, 2000). Phosphorus fertilization also promotes tree growth, but P uptake is several times lower than N. Brown and van den Driessche (2005) found that a single application of 100 kg P ha<sup>-1</sup> resulted in no greater poplar growth than 200 kg P ha<sup>-1</sup> over three years. Fertilization with potassium, zinc and copper may also be necessary to avoid deficiencies induced by N and P additions (Brockley, 2000; van den Driessche, 2000).

Biosolids application to forest species has elicited significant growth responses, especially when compared to conventional fertilization. The duration of growth response to biosolids may be longer due to increased soil organic matter, long-term nitrogen mineralization, and the availability of P, K and micronutrients which may be limiting on the site (Harrison et al., 1994). Due to high nutrient demands and high maximum growth rate and biomass production (Brown and van den Driessche, 2005), hybrid poplars are very efficient sinks of nutrients at high biosolids application rates. Biosolids cannot be incorporated by tillage on existing poplar plantations due to presence of tree roots (Lteif et al., 2007). Leaving organic amendments on the

soil surface may exacerbate N loss via ammonia volatilization (Rochette et al., 2001). Pre-plant biosolids incorporation is preferable to avoid negative effects of biosolids surface application. The method of growing poplar plantations while applying high rates of biosolids using the DRI technology is an alternative to the land application method as it provides a onetime application of nutrients sufficient for a six-year rotation (Kays et al., 1997; Felix et al., 2008).

Optimum N concentrations in upper canopy foliage for hybrid poplar were established on the level 30-35 mg N g<sup>-1</sup> (Hansen et al., 1988). While leafless biomass takes some time to respond to fertilizer applications, foliage biomass is more responsive to any changes in environmental conditions including fertilization (Gholz et al., 1991; Curran et al., 1992; Coleman et al., 2006), and may be useful to assess treatment effects at the early growth stages. Nitrogen assimilation capacity is >35 mg N g<sup>-1</sup> for high poplar stand densities > 2500 trees ha<sup>-1</sup> according to biosolids entrenchment studies by Pepperman (ERCO, 2000). However, Kays et al. (1997) determined that such densities did not produce marketable timber and recommended employing lower planting densities (e.g., 1700-2500 trees ha<sup>-1</sup>) to produce larger diameter trees more suitable for commercial markets. Despite advantages of using lower tree densities in the DRI technology, the time for roots colonization of the biosolids seams for use of potentially leachable nutrients may be environmentally detrimental. To avoid environmental consequences of possible nutrients leaching and to optimize biomass production, better precision is needed in determining poplar fertilization requirements.

The biomass production of poplar (aboveground leafless biomass) can be measured directly or estimated through a previously established growth function. Growth models belong to two major classes: statistical, which are based on descriptive characteristics, and mechanistic process based models, involving detailed description of physiological processes (Le Roux et al., 2001).

Statistical models are mostly developed for management applications and include an array of functions for poplar biomass prediction (Norby et al., 2001; Netzer et al., 2002) under various conditions. Those functions are called allometric equations and include one or more tree growth parameters (diameter at breast height, height, basal diameter, etc.) that are dependent on total leafless biomass production at the specific site. The majority of the allometric equations for biomass prediction are presented in the logarithmic form (Pastor et al., 1984; TerMikaelian and Korzukhin, 1997; Bond-Lamberty et al., 2002; Fang et al., 2007). Tree biomass predictive functions are usually presented in the general form  $y = a \times x^b$ , which is a logarithmic transform of the standard allometric growth function, most commonly used in literature (Pastor et al., 1984; TerMikaelian and Korzukhin, 1997). This eliminates the need to utilize several linear equations due to likelihood of inflection points and nonlinearity of tree growth response.

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## CHAPTER 3

### **Nitrogen and Phosphorus Leaching Potential in Deep Row Applied Biosolids for Hybrid Poplar Production in a Coastal Plain Mined Land Reclamation Site**

#### **ABSTRACT**

The effects of deep row incorporation of two biosolids types (anaerobically digested and lime stabilized) at four rates (213, 426 Mg ha<sup>-1</sup> for anaerobically digested and 328, 656 Mg ha<sup>-1</sup> for lime stabilized) and four rates of conventional fertilizer (0, 167, 337, 504 kg N ha<sup>-1</sup> yr<sup>-1</sup>) on leaching of NO<sub>3</sub>-N, NH<sub>4</sub>-N, organic-N, PO<sub>4</sub>-P, and TKP were investigated in a hybrid poplar plantation in a Coastal Plain sandy mined land reclamation site. Zero tension and suction lysimeters were installed at the site to collect leachate. Samples were collected at least monthly for 30 months between July 2006 and December 2008. The loss of N and P was determined and P binding constituents were described via regression analysis. Nitrogen leaching from the entrenched biosolids occurred initially as NH<sub>4</sub>-N, and, as nitrification progressed, mostly as NO<sub>3</sub>-N. The effects of fertilizer treatments on NO<sub>3</sub>-N and NH<sub>4</sub>-N leaching were significant, but were lower than the biosolids treatments. The leaching masses from the DRI biosolids treatments were 139-291 kg ha<sup>-1</sup> NO<sub>3</sub>-N, 61-243 kg ha<sup>-1</sup> NH<sub>4</sub>-N and 61-269 kg ha<sup>-1</sup> organic-N, while the fertilizer treatments did not differ from the 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> control. Orthophosphate and TKP leached in negligible amounts. Deep row biosolids incorporation didn't pose risks of P leaching, but did result in high N leaching below the biosolids seams.

## INTRODUCTION

More than  $7.4 \cdot 10^6$  Mg of biosolids are generated annually in the US (USEPA, 1999), and 41% of those are used as a fertilizer and soil amendment to improve soil chemical and physical properties, due to their nutrient and organic matter contents (Elliott and O'Connor, 2007). The part 503 rule (USEPA, 1993) requires that application of biosolids to agricultural land is based on nitrogen agronomic rate except for reclamation sites, where the application can be higher, under the assumption that nitrate losses to groundwater will have minimal long term negative effects following one-time application (Haering et al., 2000).

Deep row incorporation (DRI) technology is a biosolids land application method that provides a single application of nutrients sufficient for a short rotation plantation of bioenergy crops, such as hybrid poplar, and has been especially adapted for reclaiming surface mined land (Taylor et al., 1978; Kays et al., 1997; Felix et al., 2008; Felton et al., 2008). Deep row incorporation involves placement of biosolids in trenches that are immediately covered with overburden, eliminating odor problems and maintaining biosolids in a stable, anaerobic environment that reduces the transformation rate of nitrogen into soluble forms and leaching losses of nitrate (Kays et al., 1997). Thus, DRI offers a potentially environmentally beneficial approach for utilizing high rates of biosolids to restore the productivity of surface mined soils.

Once biosolids are entrenched, release of N is controlled by mineralization, in which organic forms of N are converted to ammonium-N. The process is mediated by heterotrophic microorganisms, which use organic matter as an energy source for their metabolism (He et al., 2003). Mineralization liberates large amounts of ammonium, which is quickly transformed to nitrate under aerobic conditions (Kleber et al., 2000) and may be lost via leaching into



groundwater if biosolids provide more N than can be taken up by the plants. The potential loss of N to the groundwater is highly dependent on organic matter decomposition rate, depth of groundwater level, soil porosity, and presence of low-permeability layer underneath the trenches, which would restrict leaching before the roots invade the trench and start active nutrient uptake (Sikora et al., 1980).

Phosphorus lability in the biosolids is greatly influenced by the wastewater treatment process. Lime stabilization raises biosolids pH and supplies Ca which binds P in insoluble Ca phosphates, and the addition and natural presence of Al and Fe in the wastewater treatment process results in P adsorption on sesquioxide surfaces (Maguire et al., 2001; O'Connor et al., 2004; Chinault and O'Connor, 2008).

Application of high rates of biosolids to land with no actively growing vegetation typically results in high N leaching rates (Huser, 1977; Riekerk, 1978; Stehouwer et al., 2006). The results of previous experiments on the DRI of biosolids were conducted on low permeability soils, which reduced the transformations within the biosolids seam and lacked reliable lysimetric measurements of N and P leaching (Sikora et al., 1978; Kays et al., 1997; Felton, 2008).

It was shown recently that entrenched biosolids leach high concentrations of ammonium into the vadose zone (Felton et al., 2008). Nevertheless, there is no information about the net effect on the N loss to the groundwater. Furthermore, no studies were conducted at the heavy mineral mining reclamation sites, mostly represented by the coarse-textured soils with shallow groundwater (Daniels, 1996), which are the primary reclamation sites of interest in the mid-Atlantic Coastal Plain region. It is important to understand the N and P dynamics of the DRI biosolids to assess their potential for the groundwater quality impairment.

Our objectives were to compare the effects of DRI biosolids type and annual conventional fertilizer application on N and P leaching losses from a hybrid poplar stand established in a coarse-textured heavy mineral mineland reclamation site.

## **MATERIALS and METHODS**

### **Site Description**

The study was conducted on a mineral sands (ilmenite and zircon) mine reclamation site in Dinwiddie County in Virginia, located 50 km south of Richmond. Slagle (Fine-loamy, siliceous, subactive, thermic, Aquic Hapludults), Myatt (Fine-loamy, siliceous, active, thermic, Typic Endoaquults) and Roanoke (Fine, mixed, semiactive, thermic, Typic Endoaquults) series originally covered the land prior to mining operations in this area. Post mining soil conditioning resulted from dewatering and sedimentation of sand and clay, physically separated during the mining process (Meredith, 2007). The resulting strongly stratified soil had two distinct particle size fractions: a coarse-textured material (sand) consisting of 96.1% 50 to 2000 $\mu\text{m}$  (sand), 2.0% 2 to 50 $\mu\text{m}$  (silt), and 1.9% <2  $\mu\text{m}$  (clay) and a finer-textured material (sandy clay loam) consisting of 50 to 2000 $\mu\text{m}$  (sand), 8.6% 2 to 50 $\mu\text{m}$  (silt), and 30.2% <2  $\mu\text{m}$  (clay) (Gee and Or, 2002). The soil at the site was mostly represented by the sand fraction which was overlaid by the 0.1-0.5 m layer of the sandy clay loam fraction. The sandy clay loam fraction was also present in fragmentary thin layers in the sand seam. The seasonal water table on the site fluctuated between 1.5 and 4 meters from the soil surface (Orndorff, personal communication).

### Field Experimental Design

We established the following 8 treatments: two DRI biosolids rates for each of anaerobically digested (AD) and lime stabilized (LS) biosolids, and four conventional N, P and K fertilizer rates. The eight treatments were each replicated 4 times and arranged in a randomized complete block design. Each treatment plot was 6 m wide x 15 m long and contained two rows for application of biosolids (trenches) or conventional fertilizer with a row spacing (center-to-center) of 3 m; thus, the area of each of the 32 plots is 90 m<sup>2</sup>. The rows (trenches) were also used to plant hybrid poplar.

Anaerobically digested (AD) and lime stabilized (LS) biosolids were placed in trenches excavated by backhoe at two volumetric rates: 45 cm wide×75 cm deep and 90 cm wide×75 cm deep, which was equivalent to 1125 m<sup>3</sup> ha<sup>-1</sup> and 2250 m<sup>3</sup> ha<sup>-1</sup>. The biosolids rates were the masses that fit in trenches. We calculated the rates of the biosolids as 213 dry Mg AD ha<sup>-1</sup>(AD 45 cm), 426 Mg AD ha<sup>-1</sup>(AD 90 cm), 328 dry Mg LS ha<sup>-1</sup> (LS 45 cm) and 656 dry Mg LS ha<sup>-1</sup> (LS 90 cm) after measuring the bulk densities of the biosolids types. The LS biosolids were obtained from Blue Plains Wastewater Treatment Plant, Washington, DC and were processed by lime stabilization ([http://www.epa.gov/owm/septic/pubs/alkaline\\_stabilization.pdf](http://www.epa.gov/owm/septic/pubs/alkaline_stabilization.pdf)). The AD biosolids were obtained from Alexandria Sanitation Authority, Alexandria, VA and were processed by anaerobic digestion (<http://epa.gov/OWM/mtb/multi-stage.pdf>). Chemical characteristics of AD and LS biosolids are presented in Table 1. The site was established in June and July 2006, when the biosolids were entrenched and covered with fill from the trenches, and the entire area was graded to provide a soil cover of approximately 30 cm over the biosolids trenches.

The conventional fertilizer treatments included fertilizer N surface applied and tilled into the 90 cm wide rows at 0 (Control), 168, 337 and 504 kg N ha<sup>-1</sup> yr<sup>-1</sup>. The fertilizer treatments also received basal applications of 56 kg ha<sup>-1</sup>yr<sup>-1</sup> of triple superphosphate (TSP) and 56 kg ha<sup>-1</sup> yr<sup>-1</sup> of muriate of potash based on soil test recommendations (Donohue and Heckendorn, 1994). Fertilizer N was applied annually in three applications in March, April and May 2007 in the form of ammonium nitrate, and two applications in April and May 2008 in the form of urea. Muriate of potash and TSP were applied annually with the first fertilizer N application. The fertilizer treatments were designed in order to provide the incremental levels of N for hybrid poplar and to compare the effects of conventional fertilization and the DRI on tree growth and N and P leaching.

Hybrid poplar (*Populus deltoides*×*nigra* ‘OP367’) stem cuttings were planted over the center of each biosolids trench and fertilizer row at a spacing of 3 m between plants for a total of 10 trees per plot (3×3 m, 1077 trees ha<sup>-1</sup>) on March 5-6, 2007. The cuttings were purchased from Broadacres Nursery, Inc. (18335 Butteville Road N.E., Hubbard, OR 97032) and shipped refrigerated via U.S. Postal Service to Blacksburg, VA in late February. The 30 cm long cuttings were placed about 20-25 cm into the soil and protected with 30-cm tall, 5-cm diameter staked plastic tree shelters. The herbicide Roundup™ (2-(phosphonomethylamino) acetic acid) was also sprayed around the trees once each summer in 2007 and 2008 to reduce weed competition with the poplars.

Irrigation was provided during the months of May to September 2007 and June to July 2008 via overhead sprinklers to prevent poplars from succumbing to drought stress. Daily rainfall data were obtained from the U.S. Department of Commerce National Climatic Data Center database ([www.ncdc.noaa.gov](http://www.ncdc.noaa.gov)) according to the closest weather station, located in Sussex

County, Stony Creek, VA at 36°58'N / 77°24'W and 32.0m (105') above s/l. Daily rainfall and irrigation data are presented in Figure 3-1.

### **Oxidation-Reduction Potential Measurement**

Redox potential (Eh) was measured by insertion of platinum (Pt) redox electrode at the 30 cm depth from the surface of the biosolids seam or 60 cm from the soil surface and using a silver chloride reference electrode with single annular junction (Accumet, Fisher Scientific) with the digital multimeter DM 383 (Universal Interprises, Inc. Beaverton, OR). The total of 10 Pt electrodes was used per treatment, in one of the AD 90 cm, LS 90 cm and the control, resulting in total of 30 Pt electrodes. Temperature was measured at the same depth each time Eh measurements were conducted in order to amend redox potential for standard conditions (T=25°C). Redox measurements were performed monthly between August 2006 and August 2007, and also at the end of the study in December 2008.

### **Leachate Sampling and Analysis**

Zero tension lysimeters were constructed from plastic drainage pipe sealed with a cap at one end and measuring 25 cm in diameter and 51 cm in length. Each lysimeter was filled with coarse-textured sand from the mine site and placed at 15 cm below each biosolids-filled trench and 120 cm below the surface of one of the two rows in each fertilizer treatment plot, resulting in a total of 48 zero tension lysimeters. Installation of the zero tension lysimeters was conducted in June and July 2006 at the same time with the biosolids entrenchment. Zero tension lysimeters were used to collect the leachate from the treatments in order to determine N, P and metals leaching into groundwater. Kynar tubing was extended from the bottom of the lysimeter

reservoir to the soil surface, in order to periodically evacuate the lysimeters with a portable electric pump. The tube opening at the bottom of the lysimeter was covered with a nylon fabric filter designed to prevent the transport of large particles and clogging the tube.

Suction lysimeters were constructed by attaching porous ceramic cups to the end of 5.1 cm diameter PVC pipes. The cups were sealed to the pipes with epoxy. Silica flour was placed in the bottom of each augered hole to provide a contact surface between the ceramic cup and the soil. The rest of the hole surrounding the lysimeter was filled with a 50/50 mixture of sand and bentonite, to reduce the likelihood of flow along the lysimeter pipe. Lysimeters were fitted with rubber stoppers and air-tight clips to apply vacuum for collecting water samples. Kynar tubing was used to pump water sample from the bottom of the lysimeter. Suction lysimeters were installed in August 2006 following the biosolids entrenchment to determine lateral flow adjacent to the DRI biosolids. Lysimeters were placed at the depth of 1.05 m from the soil surface between the two trenches in each of the biosolids plots at a distance of 1.5 m from the trench center. Installation in such fashion insured that the ceramic cup on the end of the suction lysimeter was at the level of the bottom of the biosolids seam. For trenches with 45 cm and 90 cm widths, the lysimeters were installed at 1.27 m and 1.05 m, respectively, from the edge of the biosolids seam. A total of 16 suction lysimeters were installed. The complete setup of the biosolids treatments is shown on Figure 3-2.

Lysimeter leachate was evacuated at least monthly for 30 months between July 2006 and December 2008. The leachate volume collected from the zero tension lysimeter was measured, as were pH with a portable HI 9023 pH meter (HANNA Instruments, Woonsocket, RI), electric conductivity (EC) and dissolved oxygen (DO) with an 85/10 YSI meter (YSI Incorporated, Yellow Springs, OH). The pH and EC of the suction lysimeter leachate were measured in the

same manner as that collected from the zero tension lysimeters. All samples were stored on ice and transported to laboratory, where dissolved nitrate ( $\text{NO}_3\text{-N}$ ), ammonium ( $\text{NH}_4\text{-N}$ ), and orthophosphate ( $\text{PO}_4\text{-P}$ ), were analyzed following filtration of leachate through  $0.45\ \mu\text{m}$  Millipore filters. Total Kjeldahl N (TKN) and total Kjeldahl phosphorus (TKP) were determined in unfiltered leachate samples. Analysis for N and P forms was conducted colorimetrically by flow injection analysis on Lachat 8000 (Lachat Instruments, Loveland, CO). Organic N was determined by the difference between TKN and  $\text{NH}_4\text{-N}$ .

Leachate from zero tension lysimeters was also analyzed for total and dissolved Al, Fe, Mn, Ca, Mg and dissolved organic carbon (DOC). The relative methods are described elsewhere (Lasley et al., in review).

### **Statistical Analysis**

Mean values and the standard errors for each variable were calculated. ANOVA tests were performed to test the treatment and time effects of the biosolids and the fertilizer treatments on leaching of N and P forms into groundwater, and leachate pH using SAS mixed procedure (SAS Institute Inc., 2008). The spatial power covariance structure was selected for the time series analysis, to meet the convergence criteria of the model. The leaching concentration data were log transformed to meet the normality assumption of statistical analysis. The tests of time and treatment effects were conducted to determine the validity of time and treatment effects on the N and P concentrations in leachate. Differences of least squares means test was also executed as a part of the mixed model analysis (full data set not shown due to its size), to determine significant treatment differences at all sampling times.

To describe the relationship between P forms and their possible binding constituents (total and dissolved Al, Fe, Ca, Mg and DOC), the log transformed data were fitted to a multiple linear regression function in REG procedure of the SAS program (SAS Institute Inc., 2008) using maximum  $R^2$  improvement technique. The significance of fit and the estimated relationship was determined by the F value of the linear regression and by coefficient of determination ( $R^2$ ) for each function, respectively. The treatment effects on the N and P forms leaching masses were analyzed with ANOVA and Tukey multiple comparisons test using the GLM procedure in SAS (SAS Institute Inc., 2008).

## **RESULTS AND DISCUSSION**

### **Leaching of N**

Deep row biosolids incorporation and conventional N fertilization resulted in high concentrations of N in the soil leachate, as detected by the zero tension (vertical leaching) and suction (lateral movement) lysimeters. During the period from July 2006 to December 2008, significant treatment by time interactions (Table 3-2) were shown for  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$  concentrations in zero tension lysimeters. Significant treatment effect was shown for  $\text{NH}_4\text{-N}$  in suction lysimeters. The concentrations of all N forms in leachate were also distinctively changing with time, as indicated by significant time effects (Table 3-2).

### **Vertical N Leaching From the DRI Biosolids**

The concentrations of  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$ , and organic N in leachate from the DRI biosolids as detected by zero tension lysimeters significantly changed with time (Table 3-3, Figure 3-3, 3-



4, 3-5). This was a result of progressive mineralization and nitrification within the biosolids seams. The lack of significant treatment effects for vertical leaching of  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$  during the periods of January-March 2007, May 2007, August-October 2007 and June-October 2008 was due to absence of leachate from the control and the fertilizer treatments at some of these dates, and also as a result of similar amounts of  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$  leaching from the DRI biosolids and the fertilizer treatments. The lack of statistically significant treatment effects on organic N leaching (Table 3-2, 3-4) was likely a result of high variability in data that inflated the variance and decreased effect significance. Increased concentrations of organic N in leachate during the first several months following biosolids entrenchment are visually apparent otherwise (Figure 3-4).

Significant treatment effects of  $\text{NH}_4\text{-N}$  leaching were detected immediately after the biosolids incorporation starting from July 2006 (Table 3-4). Differences of least squares means test among treatments showed significantly higher  $\text{NH}_4\text{-N}$  leaching ( $p < 0.05$ ) for the both rates of AD and LS treatments than the control during the period from July 2006 to June 2007. This was a result of  $\text{NH}_4\text{-N}$  release, which was initially present in the biosolids (Table 3-1) and, possibly, mineralization of organic N. The concentrations of  $\text{NH}_4\text{-N}$  rose to their high mean values of up to  $115 \text{ mg l}^{-1}$  for AD treatments and up to  $370 \text{ mg l}^{-1}$  for LS treatments (Figure 3-3), and mean organic N concentrations spiked (though not statistically significant) at  $168 \text{ mg l}^{-1}$  for the AD and  $534 \text{ mg l}^{-1}$  for the LS treatments (Figure 3-4) during July 2006 to June 2007. Similar effects of high  $\text{NH}_4\text{-N}$  and organic N in leachate within the first year following application were found in other studies utilizing high biosolids rates (Bugbee and Elliott, 1999; Felton, 2008; Peckenham et al., 2008). Relatively higher levels of organic N in the leachate from the LS treatments compared to AD were in line with the findings by Curtin et al. (1998), who showed

increased release of organic N susceptible to hydrolysis in soil after  $\text{Ca}(\text{OH})_2$  additions (Curtin et al., 1998).

In July to October 2007, the concentrations of  $\text{NH}_4\text{-N}$  and organic N in leachate from the DRI biosolids decreased to 3-25  $\text{mg l}^{-1}$  and 1-4  $\text{mg l}^{-1}$ , respectively. This was likely due to increase in temperatures, which increased the rate of nitrification, as concentrations of  $\text{NO}_3\text{-N}$  were in the range of 59-227  $\text{mg l}^{-1}$  for the DRI biosolids treatments during that period. Ammonium leaching from the DRI biosolids treatments slightly increased during spring 2008, showing significant treatment effects in March and May 2008 (Table 3-4), and was maintained within the range of 3-91  $\text{mg l}^{-1}$  for the rest of the study. These levels of  $\text{NH}_4\text{-N}$  were, however, significantly ( $P>0.05$ ) lower than the  $\text{NH}_4\text{-N}$  levels during the first year following entrenchment.

Similar to other studies on surface application of high biosolids rates and biosolids entrenchment (Huser, 1977; Sikora et al., 1978; Daniels and Haering, 1994; Stehouwer et al., 2006; Felton et al., 2008), leaching of  $\text{NO}_3\text{-N}$  significantly increased in AD and LS treatments compared to the control shortly after the biosolids application in August 2006 (Table 3-4). Significantly lower ( $P<0.0001$ ) concentrations of  $\text{NO}_3\text{-N}$  leached from AD 45 cm and AD 90 cm than from the LS 45 cm and LS 90 cm treatments during the period of September-December 2006. The mean concentrations of  $\text{NO}_3\text{-N}$  in leachate from the LS treatments were as high as 155  $\text{mg l}^{-1}$ , while  $\text{NO}_3\text{-N}$  levels in the AD treatments were only 22  $\text{mg l}^{-1}$  during that period (Figure 3-1). Nitrification rate significantly increased in the summer and fall 2007 compared to the fall 2006 period, and the biosolids treatments produced up to 163.7  $\text{mg l}^{-1}$  of  $\text{NO}_3\text{-N}$  in leachate. Nitrification of the biosolids-borne N further increased in 2008, and reached their highest values of 1118  $\text{mg l}^{-1}$  of  $\text{NO}_3\text{-N}$ , on average, in December 2008. No differences in N leaching were observed between AD and LS biosolids treatments starting January 2007, except March 2008

when the AD 45 cm treatment leached concentrations of  $\text{NO}_3\text{-N}$  significantly higher than AD 90 cm, LS 45 cm, and LS 90 cm treatments.

### **Vertical N Leaching from the Fertilizer Treatments**

Through the study period of July 2006 to December 2008 the levels of  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$  did not significantly change with time for the unfertilized control (Table 3-3). Significant effect of time on the organic N concentrations in the unfertilized control (Table 3-3) was likely due to lateral flow from the adjacent biosolids seams which resulted in increased level of organic N in September 2006. Concentrations of  $\text{NO}_3\text{-N}$  in leachate from the control remained low, below  $10 \text{ mg l}^{-1}$ , and concentrations of  $\text{NH}_4\text{-N}$  and organic N remained below  $2 \text{ mg l}^{-1}$  and  $6 \text{ mg l}^{-1}$ , respectively.

There was no significant time effect on the concentrations of  $\text{NO}_3\text{-N}$  in leachate from the  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  fertilizer treatment (Table 3-3), which remained between  $24 \text{ mg l}^{-1}$  to  $628 \text{ mg l}^{-1}$  throughout the period of the study (Figure 3-5). The elevated concentrations of  $\text{NO}_3\text{-N}$  were possibly due to high application rates of ammonium nitrate and urea that could not be assimilated by the trees and leached into groundwater (Jarvis et al., 1989; Lee and Jose, 2005). Leaching of  $\text{NO}_3\text{-N}$  from the  $168 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and  $337 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatments was weakly affected by time ( $P < 0.1$ , Table 3-3), decreasing during the summer 2007 while remaining at concentrations similar to those for the  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatment the rest of the time (Figure 3-5).

The concentrations of  $\text{NH}_4\text{-N}$  in the leachate from the  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatment increased to  $115 \text{ mg l}^{-1}$  in May 2007 and to  $64 \text{ mg l}^{-1}$  in September 2008 but declined to  $0.2\text{-}0.7 \text{ mg l}^{-1}$  during the late fall and early spring periods (Figure 3-3). The similar pattern of  $\text{NH}_4\text{-N}$  leaching occurred in the  $337 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and  $168 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatments, as indicated by

significant time effects for these treatments (Table 3-3). However,  $\text{NH}_4\text{-N}$  concentrations increased to their peaks of  $29 \text{ mg l}^{-1}$  for  $377 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and  $3 \text{ mg l}^{-1}$  for  $168 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  in the spring of 2007 following fertilization with ammonium nitrate while staying at their low levels of  $0.2 \text{ mg l}^{-1}$  to  $0.4 \text{ mg l}^{-1}$  throughout the year of 2008 following fertilization with urea. Concentrations of Organic N in the fertilizer treatments did not significantly change with time (Table 3-3) despite the peaks of  $12 \text{ mg l}^{-1}$  for  $337 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and  $15 \text{ mg l}^{-1}$  for  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  on average in the summer 2007 (Figure 3-4). The lack of statistical difference was likely a result of high variability in data. The peaks of organic N concentrations in spring 2007 were an indication of N transport from the adjacent biosolids plots, similar to such effect in the unfertilized control.

The short lived leaching of  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$  following fertilization with ammonium nitrate in 2007 is in agreement with the results by Paramazivam et al. (2000), who found that most of ammonium and nitrate left the sandy soil within several months following application. The presence of  $\text{NH}_4\text{-N}$  in leachate from the fertilizer plots during the summer 2007 period was also likely related to N transport from the adjacent biosolids seams. The lack of  $\text{NH}_4\text{-N}$  leaching response following urea application in 2008 was likely due to nitrification that resulted in little  $\text{NH}_4\text{-N}$  accumulation and high  $\text{NO}_3\text{-N}$  leaching (Raison et al., 1990). Increased  $\text{NO}_3\text{-N}$  leaching following conventional N fertilization was consistent with the findings by Lee and Jose (2005) who detected  $>10 \text{ mg l}^{-1}$   $\text{NO}_3\text{-N}$  leaching from the cottonwood plantation from the liquid application of combined urea and ammonium nitrate at the rates of  $112$  and  $224 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ .

### Lateral N Movement from the DRI Biosolids

Concentrations of  $\text{NO}_3\text{-N}$  in leachate collected by suction lysimeters significantly changed with time for AD 90 cm and LS 45 cm, and organic N changed with time for both rates of AD and LS treatments (Table 3-3). The level of  $\text{NO}_3\text{-N}$  significantly increased in the fall 2008 as compared to its level during the first 1.5 years of the study to as high as  $251 \text{ mg l}^{-1}$  for LS 45 cm treatment, on average (Figure 3-6). The levels of organic N in leachate collected by suction lysimeters from the AD treatments decreased below the detection limit of  $0.035 \text{ mg l}^{-1}$  in the fall 2008 compared to their high levels of up to  $79 \text{ mg l}^{-1}$  on average during the fall 2006 period (Figure 3-7). Lateral movement of  $\text{NH}_4\text{-N}$  was weakly affected by time for AD 45 cm and LS 90 cm treatments only ( $P=0.1$ , Table 3-3). This suggested that despite the spike within the first several months following the biosolids entrenchment (Figure 3-7), the concentrations of  $\text{NH}_4\text{-N}$  in lateral leachate were highly variable. Concentrations of  $\text{NH}_4\text{-N}$  in lateral leachate from the AD 90 cm treatment were also significantly higher than AD 45 cm and LS 90 cm in May 2008 (Table 3-5).

The levels of lateral N movement from the DRI biosolids were high, similar to the study by Felton et al. (2008). However, we observed much N transported as  $\text{NO}_3\text{-N}$  via lateral flow throughout the study period and only initial spikes of  $\text{NH}_4\text{-N}$  and organic N in the fall 2006 following biosolids incorporation. The study by Felton et al. (2008) on the fine-textured soils reported most of N lateral transport to occur as  $\text{NH}_4\text{-N}$ , while little  $\text{NO}_3\text{-N}$  lateral movement was observed. This difference was likely due to well aerated coarse-textured soils at our site, which favored nitrification.

### **Leachate pH, EC and DO in Zero Tension and Suction Lysimeters**

Leachate pH from the zero tension lysimeters was significantly affected by the treatments and significantly changed over time. No treatment or time effects were detected on leachate pH from suction lysimeters (Table 3-2). Conventional fertilization did not affect zero tension lysimeter leachate pH as did the biosolids treatments (Table 3-3). A significant decrease of pH in zero tension lysimeters from 8.2 to as low as 4.5 was due to treatments starting October 2007 (Table 4, Figure 8). Nitrification likely decreased pH in the leachate from biosolids treatments by generating protons (Qureshi et al., 2003; Peckenham et al., 2008). We didn't find any significant differences between leachate pH of the AD and LS biosolids treatments with time. Leachate in suction lysimeters was not affected by nitrification-borne acidity and pH ranged from 7.9 to 5.3 (Figure 3-9).

Significant treatment by time interaction was detected for electric conductivity, and DO responded significantly to treatment and time in zero tension lysimeter leachate, while only time affected EC in leachate from suction lysimeters (Table 3-2). Electric conductivity in zero tension lysimeter leachate significantly changed with time in both biosolids and conventional fertilizer treatments, while leachate DO only changed with time in the 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment and the biosolids treatments (Table 3-3).

Significant effects of time on suction lysimeter leachate EC were only detected for the LS biosolids treatments (Table 3-3, Figure 3-9). Increased EC in zero tension lysimeter leachate occurred immediately after the biosolids incorporation in all biosolids treatments compared to the control between September and November 2006 (Figure 3-10). This was possibly related to an initial flush of soluble salts, including NH<sub>4</sub>-N and NO<sub>3</sub>-N from the biosolids seams. The second increase in EC in zero tension lysimeter leachate from the biosolids treatments was in

January 2008 when EC reached its peak of  $8.5 \text{ mS cm}^{-1}$  in AD 45 cm and happened concurrently with an increase in leachate  $\text{NO}_3\text{-N}$ . Conventional fertilizer treatments increased EC levels in spring-summer 2007 and 2008, following annual fertilization. This was indicative of an increase in leaching concentrations, possibly KCl,  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$ . Previous studies showed dependence of EC on nutrients leaching (Heiniger et al., 2000; Santibanez et al., 2007). Despite the differences in EC from leachate in suction lysimeters the highest values didn't exceed  $1.1 \text{ mS cm}^{-1}$ .

Dissolved oxygen concentrations in zero tension lysimeter leachate were lower in the biosolids than the control treatments in December 2006 and January 2007 (Table 3-4, Figure 3-11) following the initial organic N and  $\text{NH}_4\text{-N}$  flush accompanied by organic C leaching (Lasley et al., in review), which likely resulted in increased microbial oxygen consumption and DO decrease. The levels of DO were significantly ( $P < 0.1$ ) lower in leachate from the biosolids than the control and the fertilizer treatments between April and August 2007 and March and May 2008. This showed that microbial oxygen consumption occurred during the warmer periods. The lowest DO values measured were  $2.1 \text{ mg l}^{-1}$  in AD 45 cm in September 2008. Peckenham et al. (2008) measured DO concentrations as low as  $0.1 \text{ mg l}^{-1}$  in stock-piled biosolids leachate. Lack of treatment effects in the summer 2008 sampling date was possibly a result of excavation of a mining pit adjacent to our study in late spring 2008, which likely decreased the groundwater level and facilitated atmospheric oxygen movement to deeper soil layers.

### **Oxidation-Reduction Potential in the Biosolids Seams**

Redox potential in the biosolids had significant treatment by time interaction (Table 3-2). The Eh changed with time in the AD 90 cm and LS 90 cm biosolids seams, but not in the control

(Table 3-3). Treatment effects were significant throughout the study (Table 3-5). No significant differences between Eh in AD 90 cm and LS 90 cm were observed during August 2006-August 2007, when both of the DRI biosolids were under anaerobic environment and Eh ranged between -13- -220 mV. In December 2008, LS 90 cm Eh was maintained at -250 mV and was significantly lower than AD 90 cm, whose mean Eh was 276 mV (Figure 3-12). The Eh of biosolids was significantly lower than the control. Lower redox potential in LS 90 cm was possibly a result of higher pH (Carbonell-Barrachina et al., 2000) and dispersion of the biosolids, which could have decreased macroporosity and aeration. The redox potential measured in AD 90 cm in December 2008 was adequate for oxidation of Mn and Fe, and nitrification (Masscheleyn et al., 1990).

### **Leaching of P**

No overall treatment effects were detected for  $\text{PO}_4\text{-P}$  and TKP leaching from both zero tension and suction lysimeters (Table 3-2). Significant effects of time on  $\text{PO}_4\text{-P}$  leaching in zero tension lysimeters were detected for the  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ , both AD and LS 90cm treatments, and for suction lysimeters in both LS treatments. Significant effects of time on TKP leaching in zero tension and suction lysimeters were detected for all DRI biosolids treatments (Table 3-2, 3-3). The test of treatment effects sliced by time detected few significant treatment effects on  $\text{PO}_4\text{-P}$  and TKP leaching (Table 3-4, 3-5). In November 2006, the concentrations of  $\text{PO}_4\text{-P}$  in LS 45 cm in zero tension lysimeter leachate were significantly higher than the control ( $p=0.0483$ ). In April 2007, the TKP concentrations in the suction lysimeter leachate in LS 45 cm were significantly lower than other DRI biosolids treatments. In January 2008, we detected significantly higher concentrations of TKP in the control and the  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  fertilizer



treatments than in the biosolids treatments in zero tension lysimeter leachate. In December 2008, we detected higher  $\text{PO}_4\text{-P}$  concentrations in the zero tension lysimeter leachate from the fertilizer treatments that received  $168 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  than in the LS and AD biosolids treatments. The leachate concentrations in these fertilizer treatments were 0.04 and  $0.13 \text{ mg l}^{-1} \text{ PO}_4\text{-P}$ , respectively; however, they were not significantly different from the control and the other fertilizer treatments ( $p=0.5228$  and  $0.6215$ ). There was a decrease in the  $\text{PO}_4\text{-P}$  and TKP that leached from the DRI biosolids with time (Figure 3-13, 3-14, 3-15). Concentrations of  $\text{PO}_4\text{-P}$  and TKP in suction lysimeter leachate were 2-4 times lower than in zero tension lysimeters on average, indicating that P was mostly transported by gravitational flow. Previous research demonstrated significantly higher leaching of P from the TSP- than biosolids-amended sandy soils (Elliott et al., 2002; Chinault and O'Connor, 2008), but our results didn't show any such evidence.

Regression analysis was conducted to explain which chemical variables promoted P leaching. The  $\text{PO}_4\text{-P}$  and TKP values were regressed on dissolved and total Al, Fe, Mn, Ca and Mg, and dissolved organic carbon (DOC). It showed that  $\text{PO}_4\text{-P}$  leaching was a function of DOC and dissolved Fe ( $R^2=0.2716$ ) and TKP leaching was a function ( $R^2=0.2347$ ) of DOC and total Al and Fe (Table 3-6, 3-7). These models indicated that increase in  $\text{PO}_4\text{-P}$  was associated with reduction in DOC and increase in dissolved Fe. Due to low  $R^2$ , much of the  $\text{PO}_4\text{-P}$  was likely transported in forms other than those used in the regression analysis, such as  $\text{H}_2\text{PO}_4^-$ . One of the likely ways of  $\text{PO}_4\text{-P}$  leaching was generation of acidity through nitrification, which contributed to release of significant amounts of orthophosphate associated with Ca (Maguire et al., 2001; Batziaka et al., 2008). Concentrations of TKP were inversely related to total Al and DOC, and positively related to total Fe. This indicated that some of particulate P leaching was likely

associated with precipitation of orthophosphate with Fe (III) oxyhydroxides or formation of Fe (III) phosphates (variscite) (Elliott et al., 2002; Batziaka et al., 2008; Shoher and Sims, 2009).

### **Leaching masses of N and P**

Both LS and AD treatments resulted in significant amount of  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$  and organic N leaching below the biosolids seam (Table 3-8). Because N leaching originally occurred mostly as  $\text{NH}_4\text{-N}$  and organic N, these forms combined to represent about 50% of the N leached. There was no significant difference in the amount of N forms leached between the biosolids type and rate treatments; however, the mean values of  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$  and organic N leached were highest for the LS 90 cm treatment, which received the highest biosolids rate among the DRI biosolids treatments (Table 3-1). The amount of N lost from the DRI biosolids via leaching as detected by zero tension lysimeters in July 2006-December 2008 was 261–803 kg N ha<sup>-1</sup>, which was roughly 3% of the N applied. This value is 40% of the leaching masses from the land applied biosolids at the rate of 134 Mg ha<sup>-1</sup> (Stehouwer et al., 2006). The amount of N leached from the DRI biosolids also exceeded the optimum N uptake rates by the 2 year old hybrid poplar plantation planted at the density of 10000 trees ha<sup>-1</sup> by 2.3–4.8 times (Hansen et al., 1988), and N was lost to the groundwater unreclaimed by the vegetation.

Despite the high concentrations of  $\text{NH}_4\text{-N}$ , organic N and  $\text{NO}_3\text{-N}$  in the leachate from the fertilizer treatments (Figure 3-3, 3-4, 3-5), the leaching masses were not significantly different from the unfertilized control (Table 8) and were significantly lower than from the biosolids treatments. This likely occurred due to uptake of N present in the soil in excess of hybrid poplar requirements by weeds.

There were significant DRI biosolids treatment effects on TKP leaching rates (Table 3-8), with the AD 90 cm and LS 90 cm treatments leaching more than the than AD 45 cm and LS 45 cm treatments. Both AD and LS treatments leached an order of magnitude more TKP than  $\text{PO}_4\text{-P}$ , demonstrating that colloidal P transport can be the greatest form of leached P. Siemens et al. (2008) found less than 40% of total P leaching in colloidal form. Orthophosphate leaching was significantly higher from the LS 90 cm treatment than from the  $337 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatment; however, the absolute values were extremely low. The amount of TKP lost to the groundwater from the biosolids treatments was only  $0.2\text{--}0.5 \text{ kg ha}^{-1}$ , which was  $4 \times 10^{-5}\text{--}9 \times 10^{-5}\%$  of the total P loading rates. This is consistent with the results of a study by Siddique and Robinson (2004), who found that P release decreased in the order  $\text{KH}_2\text{PO}_4$  and cattle slurry > poultry litter > biosolids. This indicated that the deep row incorporated LS and AD biosolids, applied in excess P requirements, are able to retain phosphorus and with only negligible risks of P leaching into groundwater in the coarse-textured soils with limited P-sorbing capacity.

## CONCLUSIONS

Sandy mining site reclamation with deep row application of biosolids pose risks to groundwater quality due to N leaching, initially as  $\text{NH}_4\text{-}$  and organic-N and, later, as  $\text{NO}_3\text{-N}$ . Deep row incorporation of biosolids at these rates also decreases pH in the vadose zone under the biosolids seams due to extensive nitrification. However, entrenched biosolids possessing high P-binding capacity, poses little risk of P leaching into groundwater, which is remarkable for the coarse-textured soils with poor P retention. Deep row entrenching of biosolids in coarse-textured media should not be employed as a mineland reclamation technique because the anaerobic

conditions required to reduce mineralization and nitrification cannot be maintained in such permeable soils.

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## TABLES

Table 3-1. Chemical characteristics of anaerobically digested (AD) and lime stabilized (LS) biosolids used in the study

Biosolids	Entrenched mass (dry Mg ha <sup>-1</sup> )		Value for characteristic						
	Trench width		Dry matter content (%)	pH	Organic C (%)	Organic N (g kg <sup>-1</sup> )	NH <sub>4</sub> -N (g kg <sup>-1</sup> )	NO <sub>3</sub> -N (g kg <sup>-1</sup> )	Total P (g kg <sup>-1</sup> )
	45 cm	90 cm							
AD	213	426	37.3	8.5	30.7	40.20	12.90	0.01	26.53
LS	328	656	51.5	12.3	33.0	42.53	1.97	0.02	8.67

Table 3-2. Overall treatment and time effects on N and P forms, pH, electrical conductivity of leachate collected by zero tension and suction lysimeters and oxidation-reduction potential throughout the the experiment (July 2006-December 2008).

	Response Variable	p-values		
		Treatment	Time	Treatment x Time
		p-values		
Zero tension lysimeters	NO <sub>3</sub> -N	<.0001	<.0001	<.0001
	NH <sub>4</sub> -N	<.0001	<.0001	0.0247
	Organic-N	0.7247	<.0001	0.9782
	PO <sub>4</sub> -P	0.1249	<.0001	0.5051
	TKP	0.7869	<.0001	0.9819
	pH	<.0001	<.0001	0.0519
	EC	0.0011	<.0001	0.0006
	DO	<.0001	<.0001	0.7668
Suction lysimeters	NO <sub>3</sub> -N	0.7144	0.0436	0.3907
	NH <sub>4</sub> -N	0.0142	0.0007	0.98
	Organic-N	0.7302	<0.0001	0.9510
	PO <sub>4</sub> -P	0.1297	<.0001	0.8402
	TKP	0.7302	<.0001	0.951
	pH	0.6173	0.3114	0.9859
	EC	0.7011	0.0001	0.3163
Redox	Eh	<0.0001	0.0962	<0.0001

P-values indicate significance of treatment and time effects and their interaction. Analysis conducted in PROC MIXED procedure in SAS. All response variables are log transformed.

Table 3-3. Effects of time on N and P forms, pH, electrical conductivity of leachate collected by zero tension and suction lysimeters and oxidation-reduction potential of anaerobically digested (AD) and lime stabilized (LS) deep row incorporated (DRI) biosolids and conventional fertilizer treatments throughout the experiment (July 2006-December 2008).

		Control	168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	504kg N ha <sup>-1</sup> yr <sup>-1</sup>	AD 45cm	AD 90cm	LS 45 cm	LS 90 cm
Zero tension lysimeters		DF							
	Trt x Time	16	13	13	14	27	27	26	26
	Total	664	664	664	664	664	664	664	664
		p-values							
	NO <sub>3</sub> -N	0.9943	0.0751	0.0583	0.6099	<.0001	<.0001	<.0001	<.0001
	NH <sub>4</sub> -N	0.8668	0.0007	0.0291	0.0003	0.0339	0.0011	<.0001	0.0051
	Organic-N	0.017	0.1029	0.1515	0.3728	<.0001	<.0001	<.0001	<.0001
	PO <sub>4</sub> -P	0.5168	0.2472	0.0887	0.0027	0.0078	<.0001	0.193	0.0033
	TKP	0.0175	0.1039	0.1564	0.3735	<.0001	<.0001	<.0001	<.0001
	pH	0.9763	0.9206	0.7972	0.2483	<.0001	<.0001	<.0001	<.0001
EC	0.6821	0.0038	0.0311	0.0143	<.0001	<.0001	<.0001	<.0001	
DO	0.0578	0.1934	0.0628	0.0100	<.0001	<.0001	<.0001	<.0001	
Suction lysimeters		DF							
	Trt x Time	-	-	-	-	10	16	17	12
	Total	-	-	-	-	74	74	74	74
		p-values							
	NO <sub>3</sub> -N	-	-	-	-	0.6832	0.0474	0.036	0.5108
	NH <sub>4</sub> -N	-	-	-	-	0.1049	0.1463	0.5587	0.1038
	Organic-N	-	-	-	-	<.0001	0.0184	<.0001	0.0004
	PO <sub>4</sub> -P	-	-	-	-	0.1312	0.0964	<.0001	0.0149
	TKP	-	-	-	-	<.0001	0.0184	<.0001	0.0004
	pH	-	-	-	-	0.278	0.425	0.9771	0.822
EC	-	-	-	-	0.1299	0.0747	0.0128	0.0081	
Redox	Eh	0.8224	-	-	-	<0.0001	-	0.0001	

Table 3-4. Effects of anaerobically digested (AD) and lime stabilized (LS) deep row incorporated biosolids (DRI) and conventional fertilizer treatments on N and P forms, pH, EC and DO in leachate collected by zero tension lysimeters throughout the experiment (July 2006-December 2008).

Time	Trt	N	NO <sub>3</sub> -N	NH <sub>4</sub> -N	Organic-N	PO <sub>4</sub> -P	TKP	pH	EC	DO
		DF	p-values							
7/14/2006	5	664	0.3572	<.0001	0.6818	0.7019	0.6773	0.2292	0.9566	-
8/10/2006	6	664	<.0001	<.0001	0.7893	0.9383	0.7958	0.942	0.1573	-
9/8/2006	5	664	<.0001	0.4631	0.7333	0.6395	0.7337	0.9774	0.0059	-
10/6/2006	4	664	<.0001	0.1397	0.9936	0.6033	0.9936	0.9296	0.005	-
11/3/2006	4	664	<.0001	0.0057	0.3093	0.0393	0.312	0.9799	0.0175	-
12/1/2006	4	664	0.0041	0.0352	0.6133	0.2164	0.6159	0.9987	0.5949	0.0083
12/15/2006	4	664	0.0086	0.1502	0.0729	0.5639	0.0734	0.9721	0.5486	0.5301
1/5/2007	4	664	0.0021	0.046	0.606	0.2515	0.6099	0.9134	0.6534	0.9009
1/19/2007	4	664	0.7544	0.6264	0.0634	0.1137	0.0963	0.6539	0.5097	0.0178
2/9/2007	3	664	0.0426	0.9957	0.9516	0.2682	0.8124	0.9202	0.8429	0.7204
3/2/2007	3	664	0.1943	0.9351	0.0178	0.2862	0.0149	0.2658	0.4968	0.353
3/23/2007	6	664	0.0452	0.0008	0.9337	0.5116	0.9315	0.655	0.8258	0.4031
4/13/2007	7	664	0.1066	0.0011	0.083	0.8829	0.0987	0.1244	0.9133	0.0017
5/11/2007	5	664	0.5058	0.1876	0.9533	0.7162	0.9557	0.2835	0.7292	0.0952
6/8/2007	7	664	0.464	0.0312	0.9998	0.2301	0.9998	0.2018	0.6553	0.074
7/10/2007	7	664	0.5984	0.3773	1	0.9641	1	0.1439	0.8297	0.006
8/9/2007	6	664	0.7274	0.3115	0.9997	0.8256	0.9997	0.2765	0.9589	0.0792
9/7/2007	4	664	0.7075	0.6141	0.997	0.9831	0.997	0.1996	0.6509	0.7851
10/12/2007	4	664	0.3764	0.9691	0.9997	0.798	0.9997	0.0846	0.7972	0.3941
1/23/2008	7	664	<.0001	0.1085	0.0032	0.8954	0.0032	0.0132	0.0002	0.4601
3/24/2008	7	664	<.0001	<.0001	0.266	0.2361	0.2668	0.0058	<.0001	0.0944
5/2/2008	7	664	<.0001	<.0001	0.7755	0.2663	0.7768	0.0002	<.0001	0.0432
6/5/2008	3	664	0.77	0.6165	0.9975	0.4221	0.9975	0.6611	0.0663	0.8181
7/11/2008	4	664	0.9953	0.8651	0.996	0.3674	0.996	0.0004	0.0363	0.4784
9/18/2008	5	664	0.7659	0.1001	0.9657	0.5866	0.9656	0.0163	0.0436	0.1402
10/23/2008	3	664	0.8082	0.3926	0.9083	0.314	0.9073	0.4751	0.0203	0.9235
12/4/2008	7	664	0.0377	0.0368	0.9786	0.3905	0.9788	0.0041	0.0013	0.7942
12/28/2008	7	664	<.0001	<.0001	0.928	0.0103	0.9307	<.0001	0.0004	0.114

P-values indicate significance of treatment effects at each sampling time. Analysis conducted in PROC MIXED procedure in SAS. All response variables are log transformed.

Table 3-5. Effects of anaerobically digested (AD) and lime stabilized (LS) deep row incorporated biosolids (DRI) treatments on N and P forms, pH and EC in leachate collected by suction lysimeters as well as the DRI biosolids and unfertilized control treatments effects on oxidation-reduction potential throughout the experiment (July 2006-December 2008).

Time	Trt	N	NO <sub>3</sub> -N	NH <sub>4</sub> -N	Organic-N	PO <sub>4</sub> -P	TKP	pH	EC	Eh
	DF	p-values								
7/14/2006	-	-	-	-	-	-	-	-	-	-
8/10/2006	-	-	-	-	-	-	-	-	-	<0.0001
9/8/2006	3	74	0.0536	0.4162	0.9933	0.8313	0.9933	0.9404	0.5418	<0.0001
10/6/2006	2	74	0.9162	0.4778	0.9949	0.6288	0.9949	0.8336	0.4236	<0.0001
11/3/2006	3	74	0.4298	0.1557	0.9973	0.7861	0.9973	0.4051	0.2933	<0.0001
12/1/2006	3	74	0.7257	0.255	0.9707	0.631	0.9707	0.1659	0.3264	<0.0001
12/15/2006	3	74	0.1751	0.1886	0.1938	0.2113	0.1938	0.4768	0.0165	-
1/5/2007	3	74	0.511	0.1243	0.4186	0.6973	0.4186	0.639	0.6836	-
1/19/2007	3	74	0.5894	0.7911	0.8216	0.3641	0.8216	0.7929	0.2255	<0.0001
2/9/2007	2	74	0.9531	0.624	0.7757	0.6139	0.7757	0.9955	0.6886	-
3/2/2007	3	74	0.9666	0.7934	0.9885	0.9293	0.9885	0.5238	0.8954	<0.0001
3/23/2007	2	74	0.8656	0.934	0.9769	0.8264	0.9769	0.9635	0.8579	-
4/13/2007	2	74	0.6464	0.8558	0.0136	0.2081	0.0136	0.4741	0.7255	<0.0001
5/11/2007	-	-	-	-	-	-	-	-	-	<0.0001
6/8/2007	3	74	0.6012	0.7349	0.9995	0.9949	0.9995	0.7662	0.8831	<0.0001
7/10/2007	-	-	-	-	-	-	-	-	-	<0.0001
8/9/2007	-	-	-	-	-	-	-	-	-	<0.0001
9/7/2007	-	-	-	-	-	-	-	-	-	-
10/12/2007	-	-	-	-	-	-	-	-	-	-
1/23/2008	-	-	-	-	-	-	-	-	-	-
3/24/2008	-	-	-	-	-	-	-	-	-	-
5/2/2008	3	74	0.2542	0.0322	0.1025	0.2019	0.1025	0.8693	0.4105	-
6/5/2008										-
7/11/2008	1	74	0.7573	0.6513	0.9689	0.5483	0.9689	0.7572	0.703	-
9/18/2008	-	-	-	-	-	-	-	-	-	-
10/23/2008	-	-	-	-	-	-	-	-	-	-
12/4/2008	1	74	0.1889	0.9437	0.783	0.1558	0.783	0.8695	0.0127	-
12/28/2008	3	74	0.1424	0.3774	0.9996	0.0713	0.9996	0.3491	0.2166	<0.0001

P-values indicate significance of treatment effects at each sampling time. Analysis conducted in PROC MIXED procedure in SAS. All response variables are log transformed.

Table 3-6. Regression analysis for TKP and PO<sub>4</sub>-P concentrations in leachate as a function of possible binding constituents (Al, Ca, Fe, Mg, DOC).\*

Independent variable	Model	Error	Total	p-value	R <sup>2</sup>
TKP	8	74	82	0.0084	0.2347
PO <sub>4</sub> -P	8	74	82	0.002	0.2716

Analysis conducted using the maximum R<sup>2</sup> improvement technique of PROC REG procedure in SAS.

\*All dependent and independent variables were log transformed.

Table 3-7. Regression coefficients for the TKP and PO<sub>4</sub>-P binding constituents in leachate collected by zero tension lysimeters on selected dates between August 2006 and October 2007.\*

Dependent variable, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>			PO <sub>4</sub> -P, mg l <sup>-1</sup>		
	parameter estimate	SE	p-value	parameter estimate	SE	p-value
Intercept	-3.29317	1.27608	0.0118	-3.32996	0.98291	0.0011
Al <sub>total</sub>	-0.26498	0.13418	0.050	-	-	-
Fe <sub>total</sub>	0.17701	0.08857	0.0493	-	-	-
Fe <sub>dissolved</sub>	-	-	-	0.30256	0.105	0.0052
DOC	-0.2244	0.09014	0.015	-0.17654	0.06943	0.0131

SE – Standard Error for the parameter estimates.

\*All dependent and independent variables were log transformed.

Table 3-8. Leaching masses of N and P forms over the study period (July 2006 to December 2008).

Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	Organic-N	PO <sub>4</sub> -P	Total Kjeldahl- P
	-----kg/ha-----			-----g/ha-----	
Control	0.51 b	2.68 b	0.85 b	9 ab	40 c
168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	27.36 b	2.81 b	0.92 b	10 ab	49 c
337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	24.51 b	3.84 b	1.02 b	9 b	43 c
504 kg N ha <sup>-1</sup> yr <sup>-1</sup>	15.44 b	3.80 b	1.35 b	10 ab	45 c
AD 45 cm	139.38 a	61.36 a	61.12 a	16 ab	133 b
AD 90 cm	242.51 a	153.10 a	91.90 a	26 ab	453 a
LS 45 cm	192.85 a	104.66 a	145.39 a	68 ab	177 b
LS 90 cm	291.16 a	242.61 a	269.33 a	66 a	556 a

Treatment means in each column followed by the same letter are not significantly different at p<0.05. Tukey's Studentized Range (HSD) test performed in PROC GLM procedure on log transformed (NH<sub>4</sub>-N, organic-N, PO<sub>4</sub>-P, TKP) and square root transformed (NO<sub>3</sub>-N) data.

## FIGURES

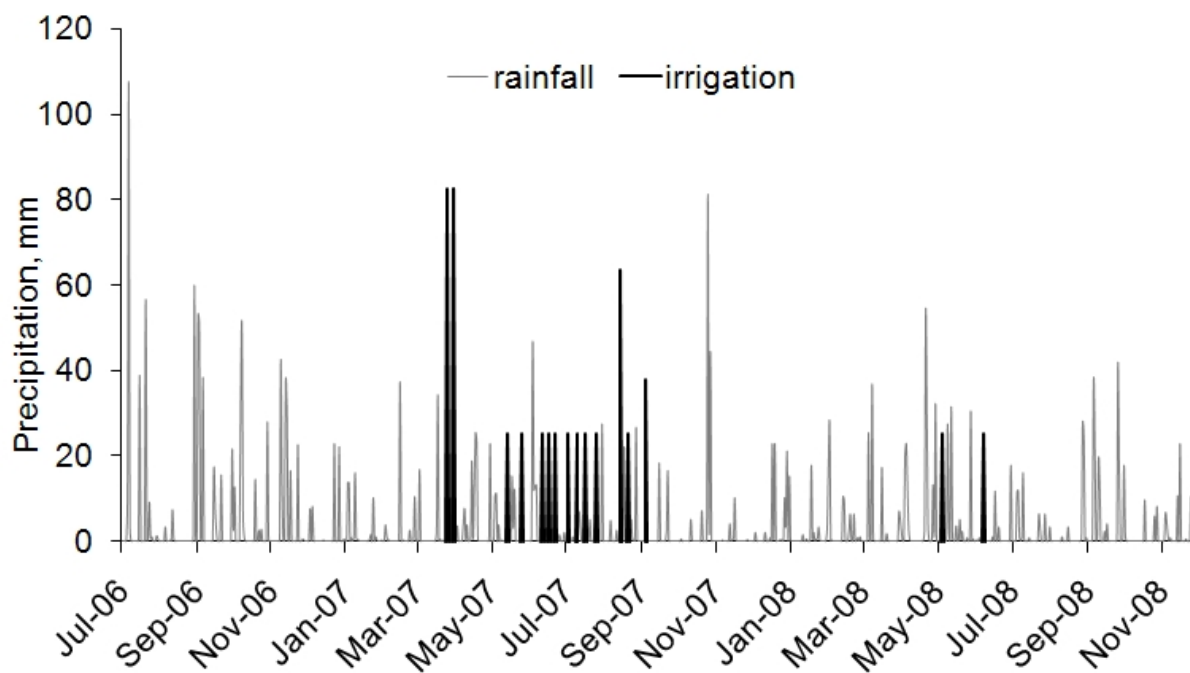


Figure 3-1. Rainfall and irrigation over the course of the study between July 2006 and December 2008.

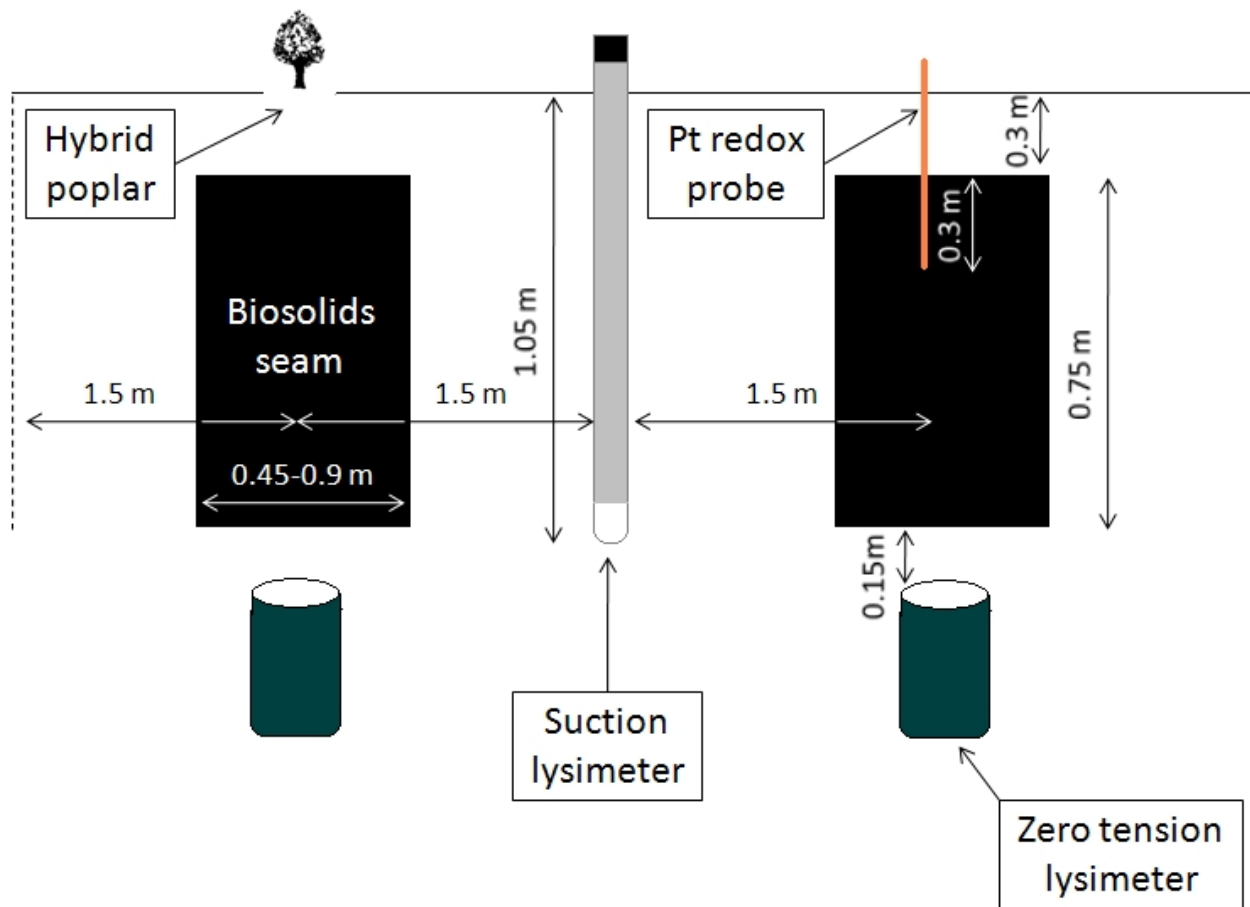


Figure 3-2. Deep row incorporated biosolids plot setup and dimensions.

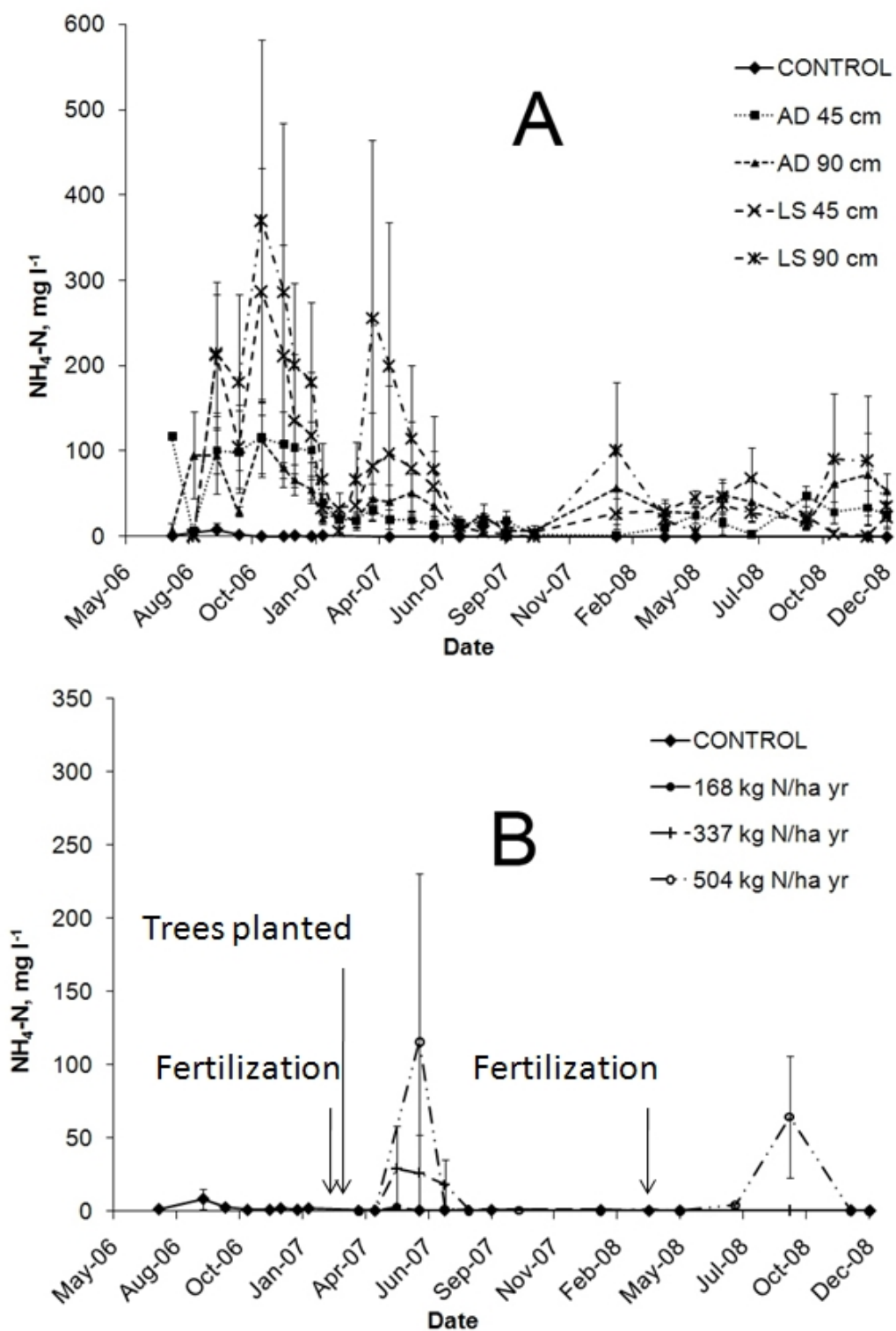


Figure 3-3. Concentrations of  $\text{NH}_4\text{-N}$  in leachate collected by zero tension lysimeters from the DRI biosolids treatments (A) and conventional fertilizer treatments (B) through the study period (July 2006-December 2008). Bars represent standard errors.



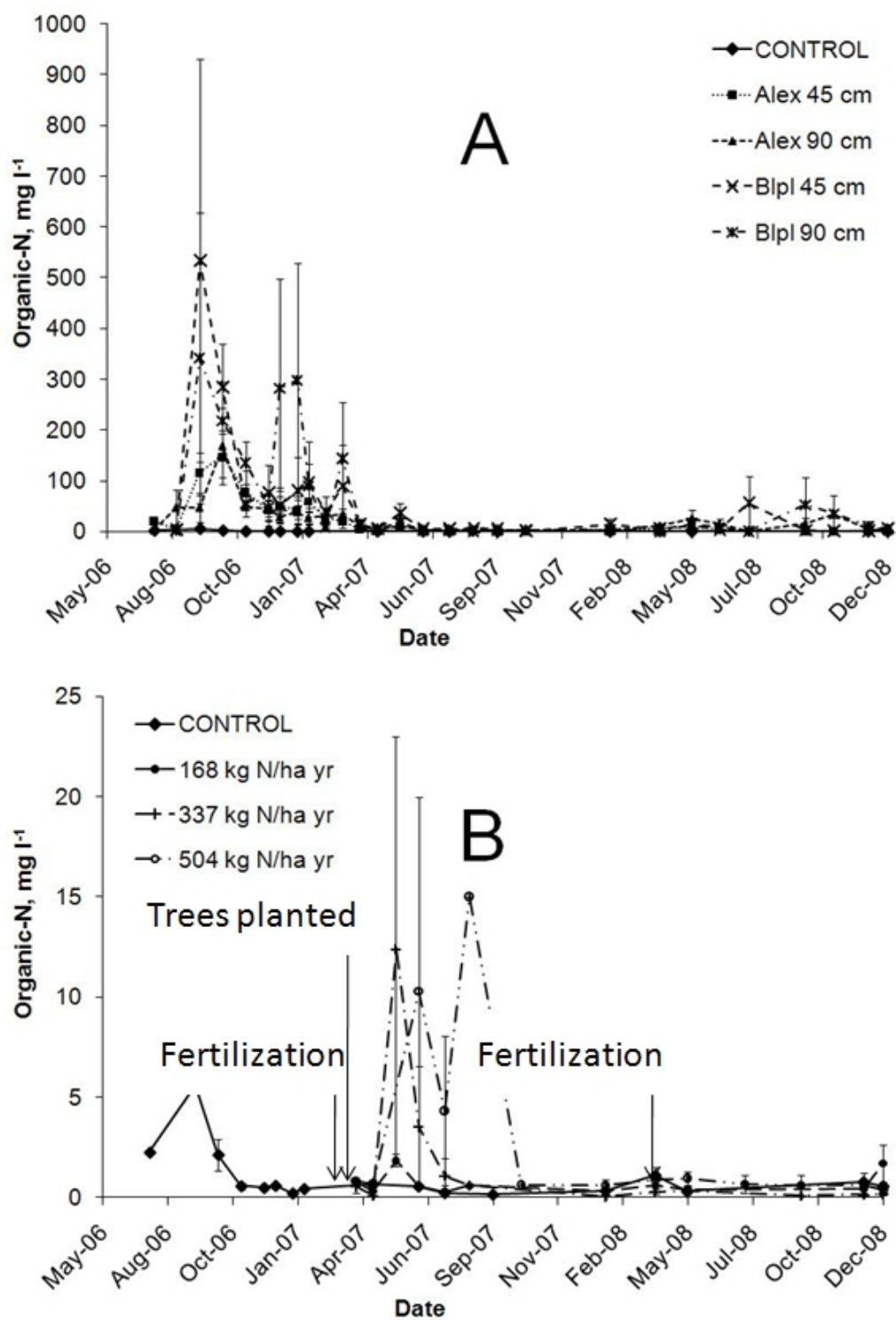


Figure 3-4. Concentrations of organic-N in leachate collected by zero tension lysimeters from the DRI biosolids treatments (A) and conventional fertilizer treatments (B) through the study period (July 2006-December 2008). Bars represent standard errors.

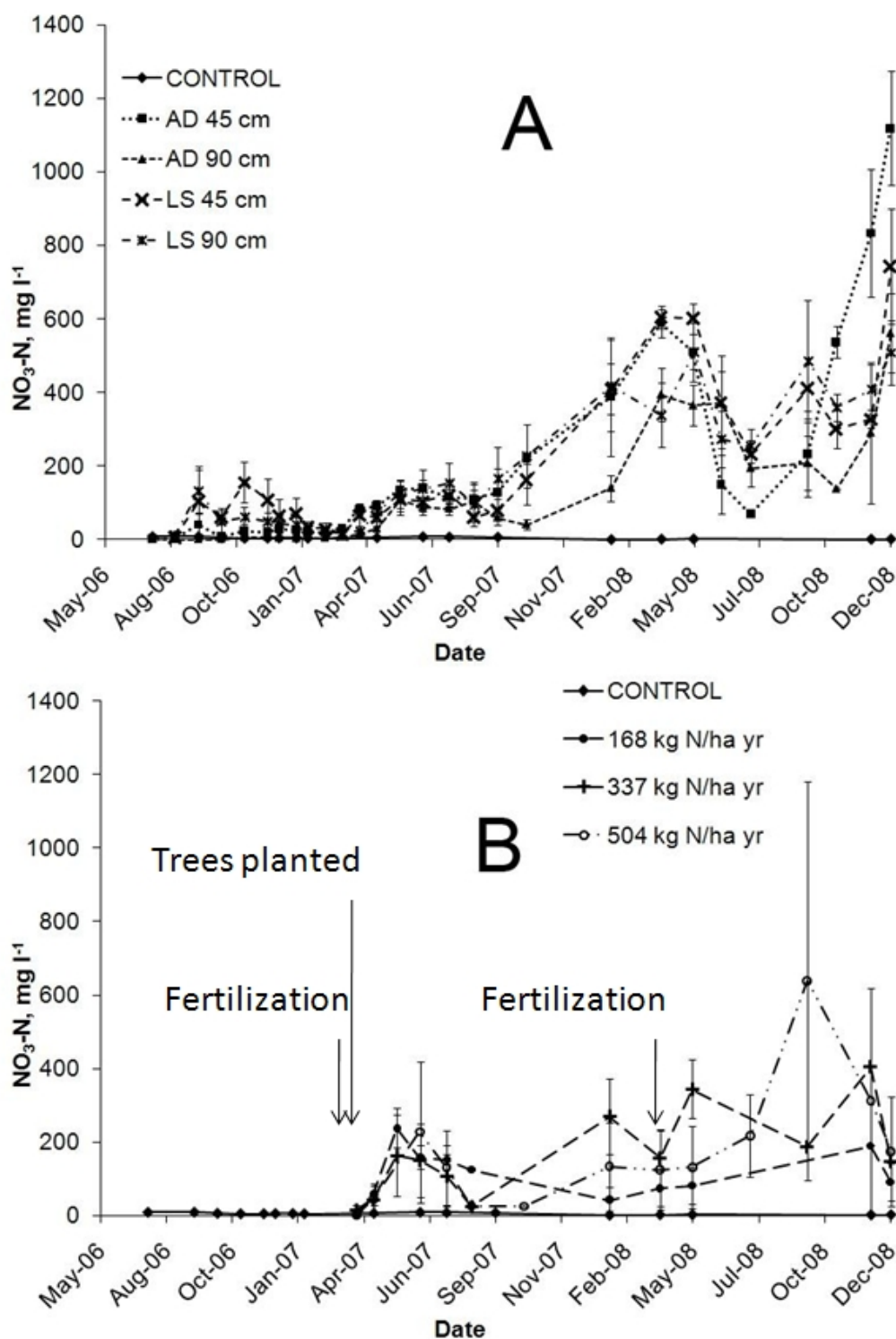


Figure 3-5. Concentrations of NO<sub>3</sub>-N in leachate collected by zero tension lysimeters from the DRI biosolids treatments (A) and conventional fertilizer treatments (B) through the study period (July 2006-December 2008). Bars represent standard errors.

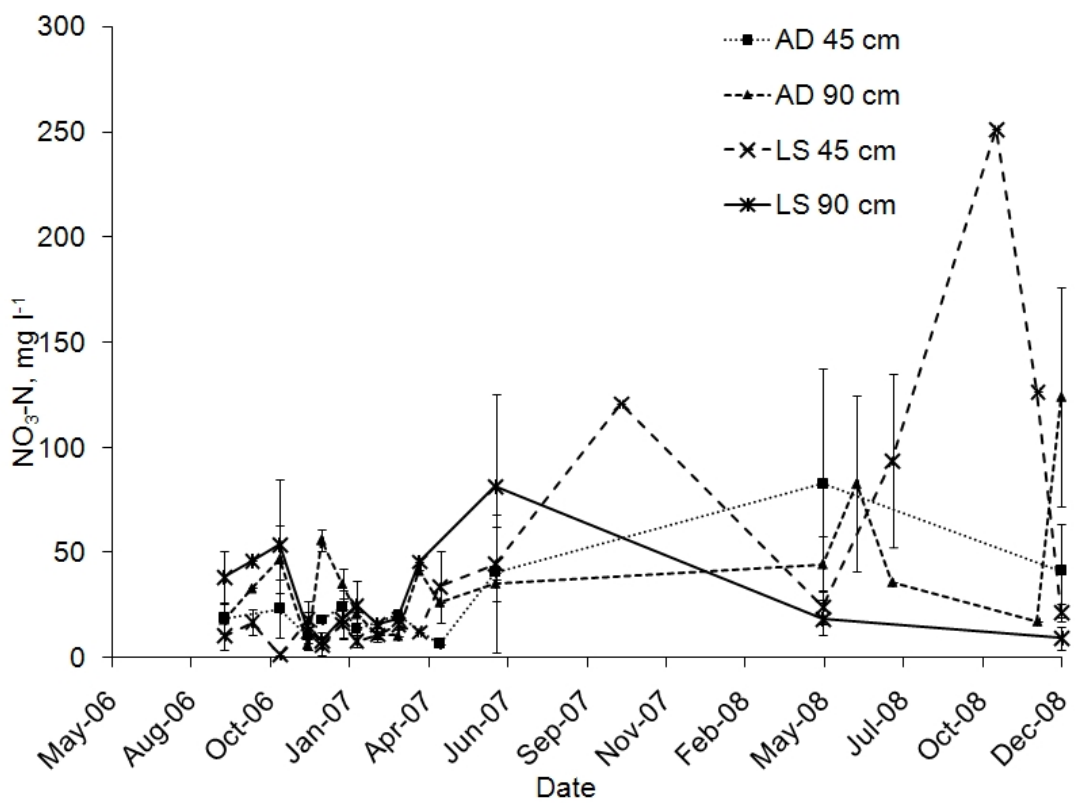


Figure 3-6. Concentrations of NO<sub>3</sub>-N in leachate collected by suction lysimeters from the DRI biosolids treatments through the study period (September 2006-December 2008). Bars represent standard errors.

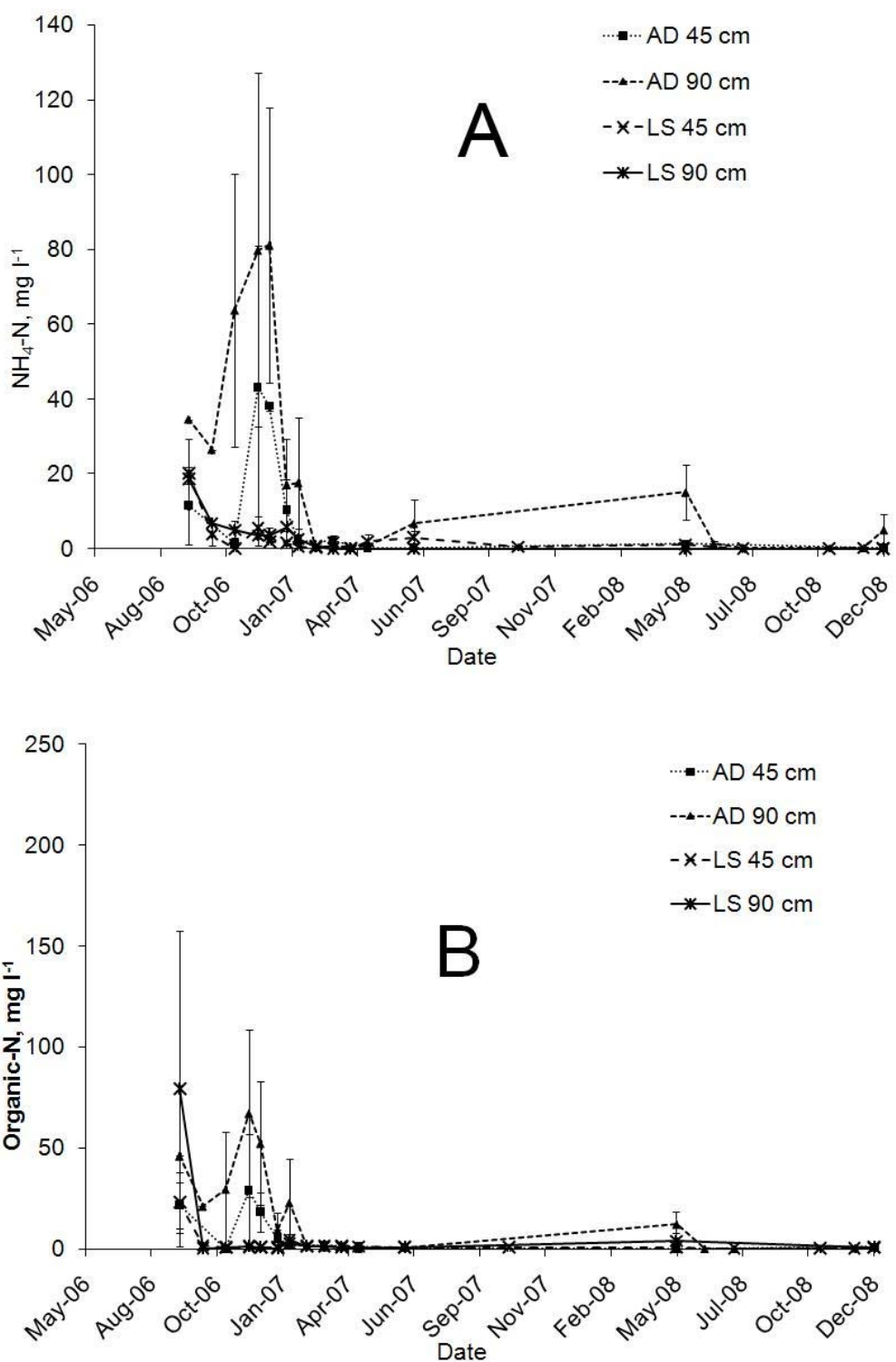


Figure 3-7. Concentrations of NH<sub>4</sub>-N (A) and organic-N (B) in leachate collected by suction lysimeters from the DRI biosolids treatments through the study period (September 2006-December 2008). Bars represent standard errors.

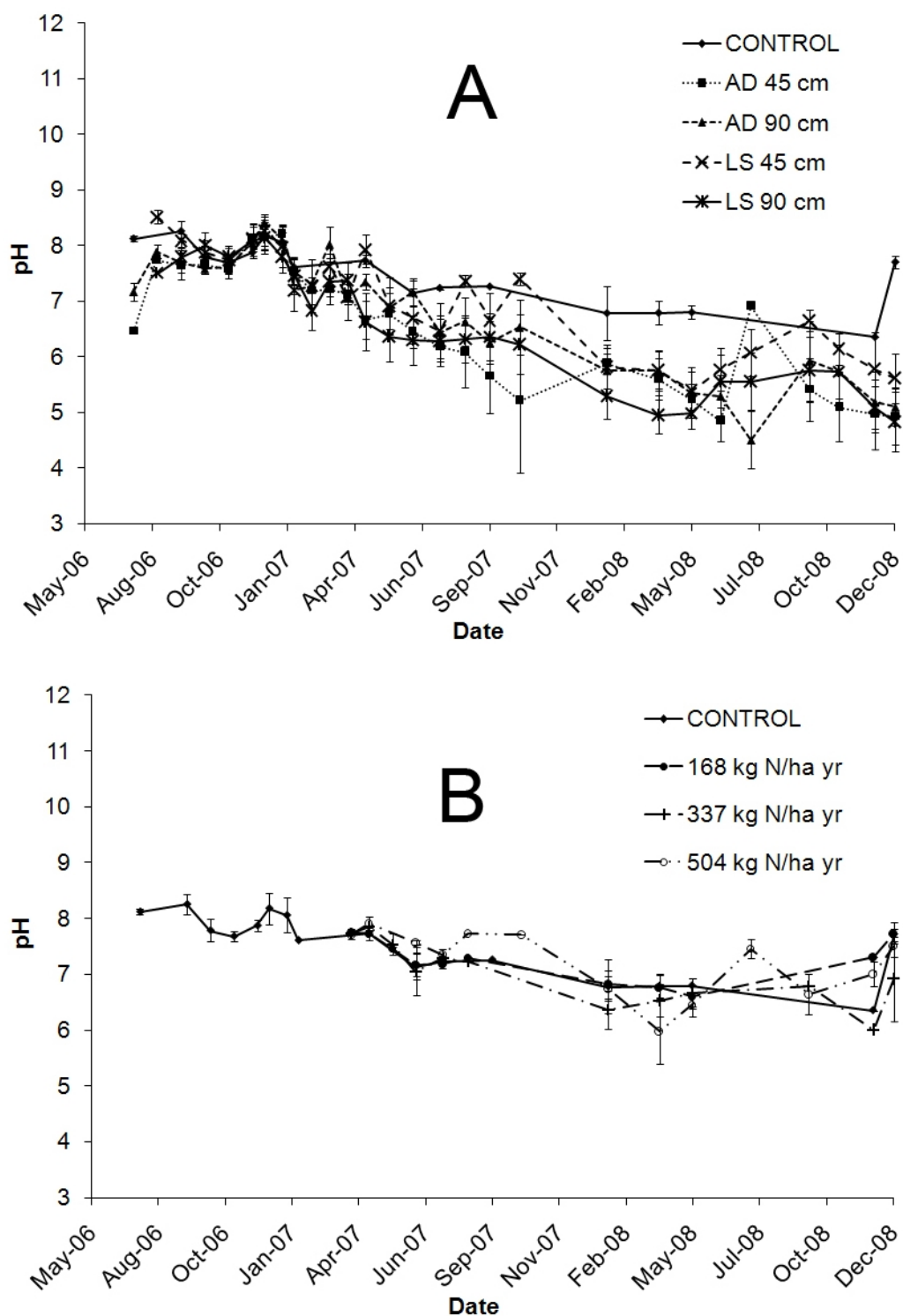


Figure 3-8. pH of leachate collected by zero tension lysimeters from the DRI biosolids treatments (A) and conventional fertilizer treatments (B) through the study period (July 2006-December 2008). Bars represent standard errors.

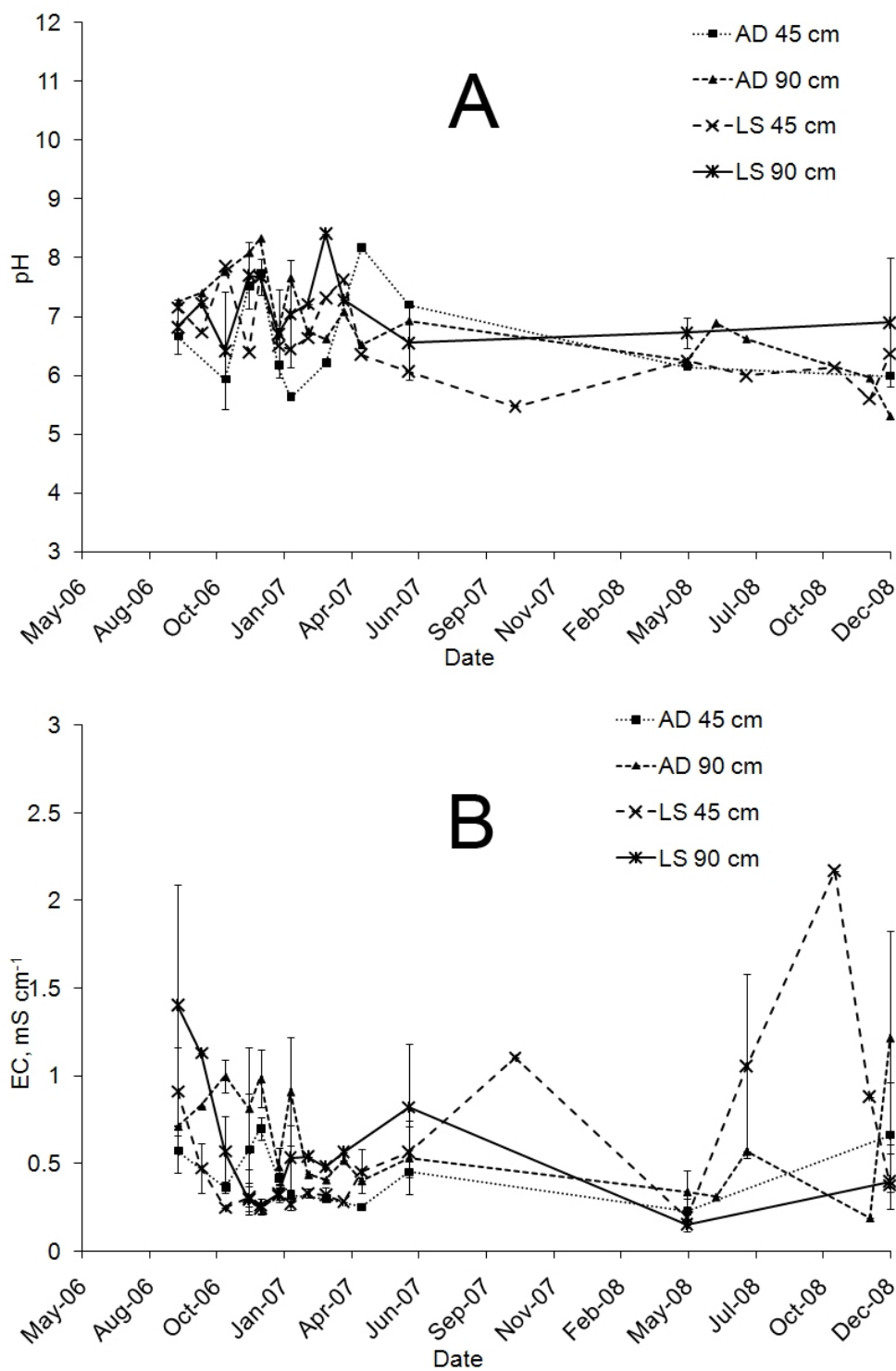


Figure 3-9. pH (A) and EC (B) of leachate collected by suction lysimeters from the DRI biosolids treatments through the study period (September 2006-December 2008). Bars represent standard errors.

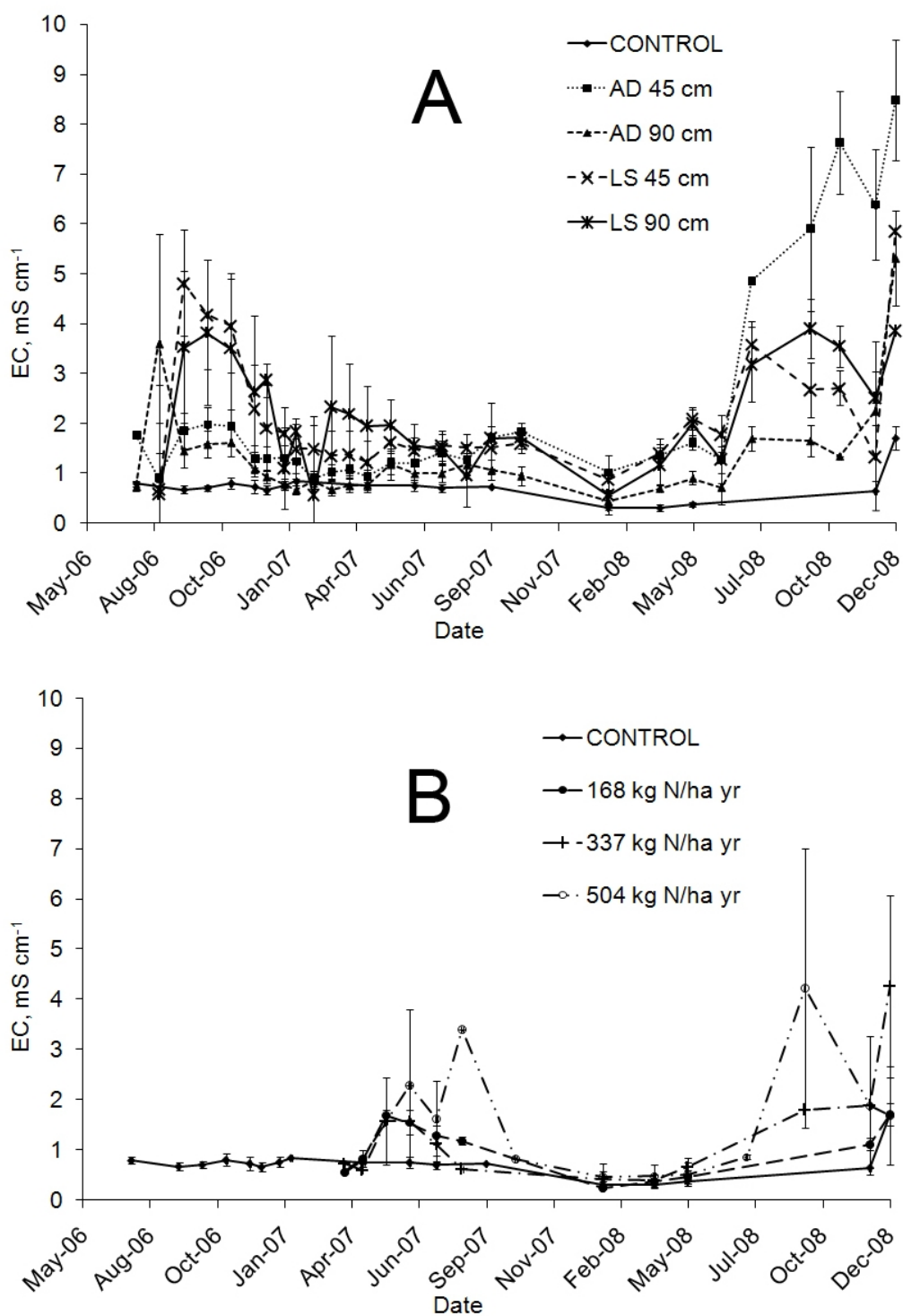


Figure 3-10. Electric conductivity (EC) of leachate collected by zero tension lysimeters from the DRI biosolids treatments (A) and conventional fertilizer treatments (B) through the study period (July 2006-December 2008). Bars represent standard errors.

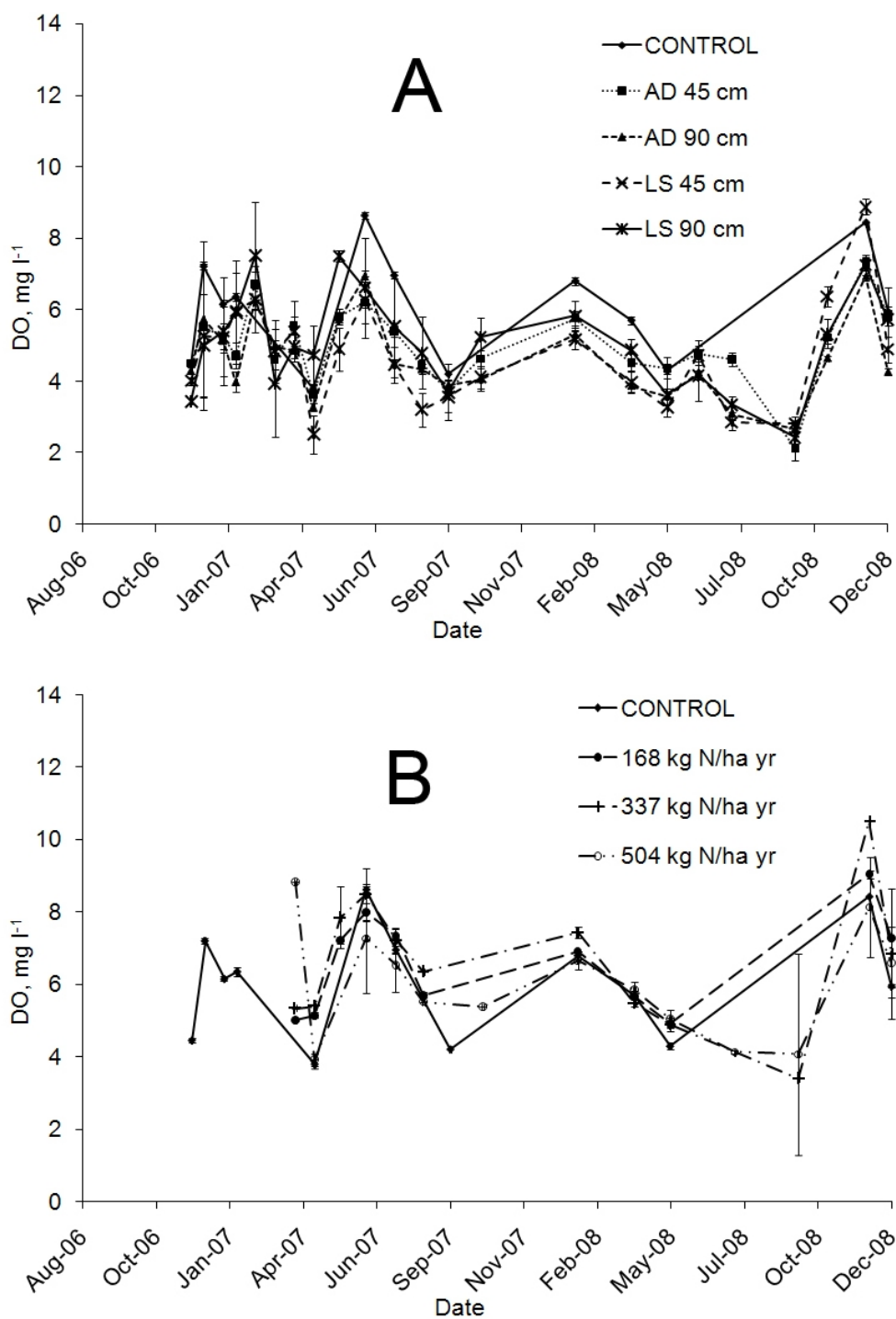


Figure 3-11. Concentrations of dissolved oxygen (DO) in leachate collected by zero tension lysimeters from the DRI biosolids treatments (A) and conventional fertilizer treatments (B) through the study period (July 2006-December 2008). Bars represent standard errors.



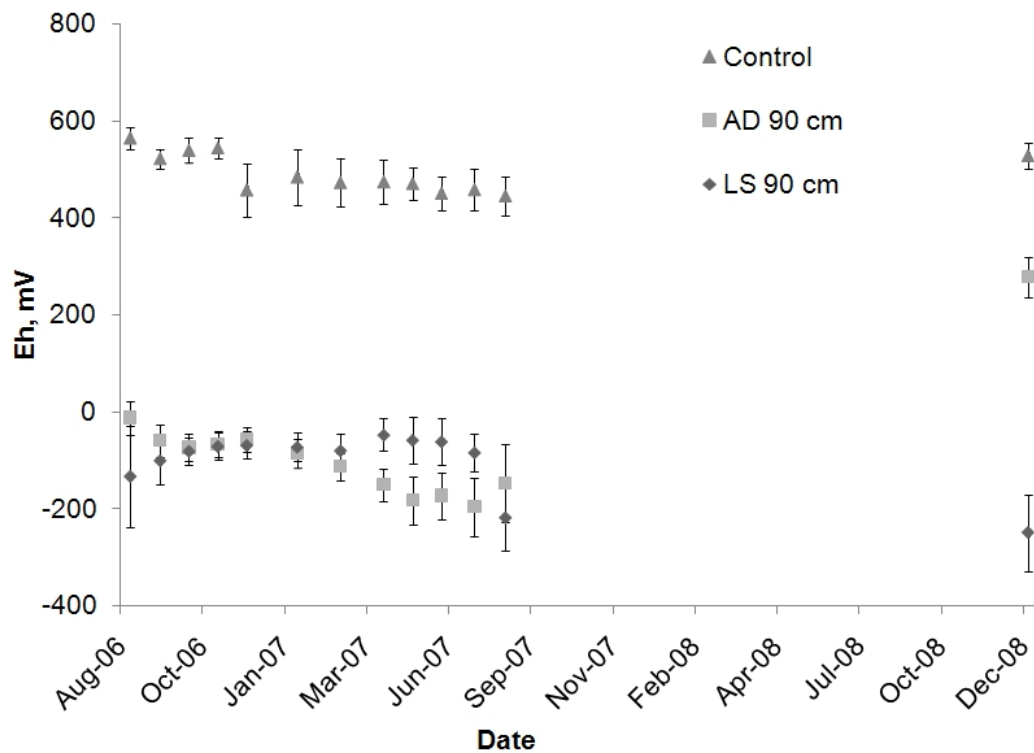


Figure 3-12. Oxidation-reduction potential at 30 cm depth of the DRI biosolids seams and the control treatments through the study period (August 2006-December 2008). Bars represent standard errors.

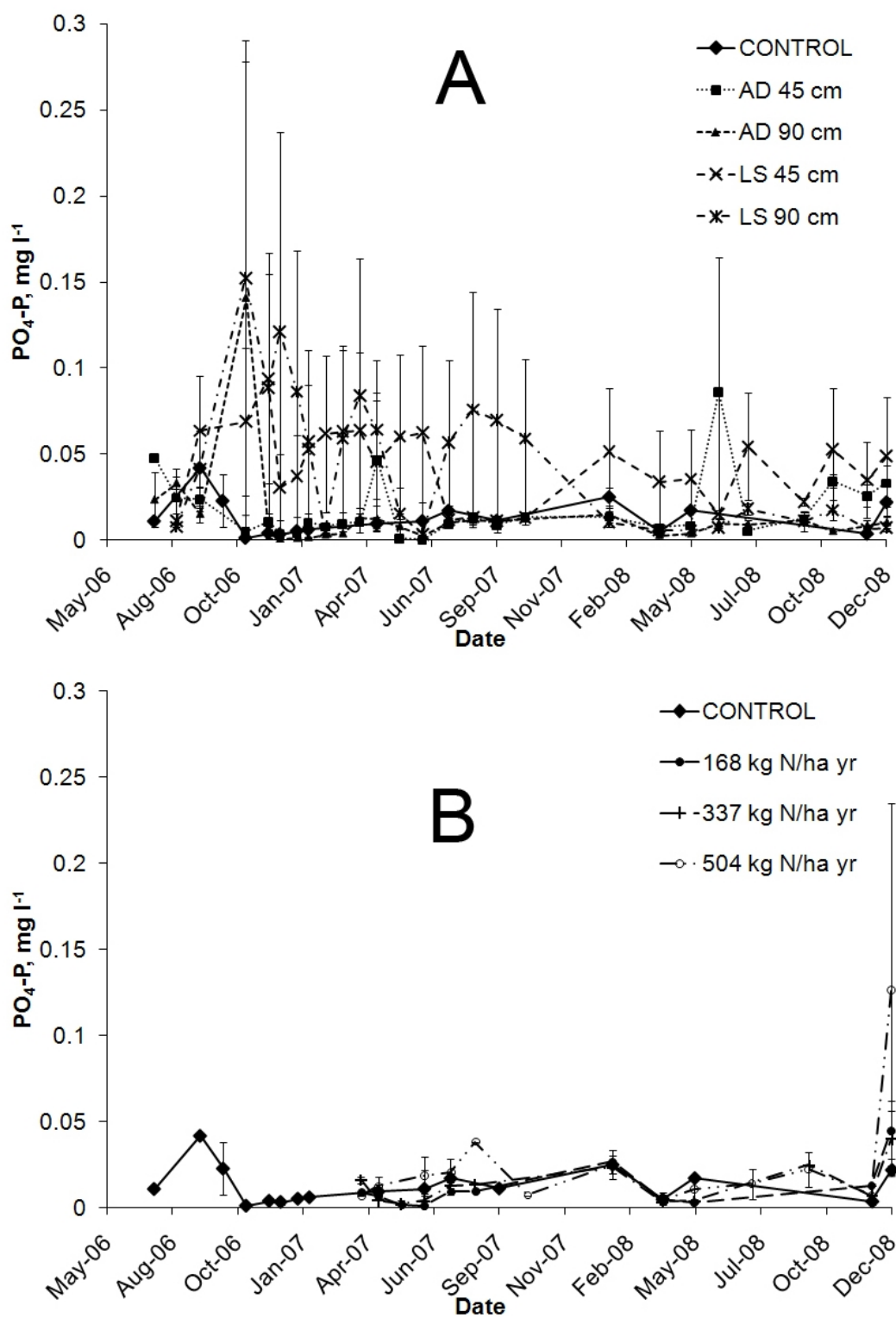


Figure 3-13. Concentrations of PO<sub>4</sub>-P in leachate collected by zero tension lysimeters from the DRI biosolids treatments (A) and conventional fertilizer treatments (B) through the study period (July 2006-December 2008). Bars represent standard errors.

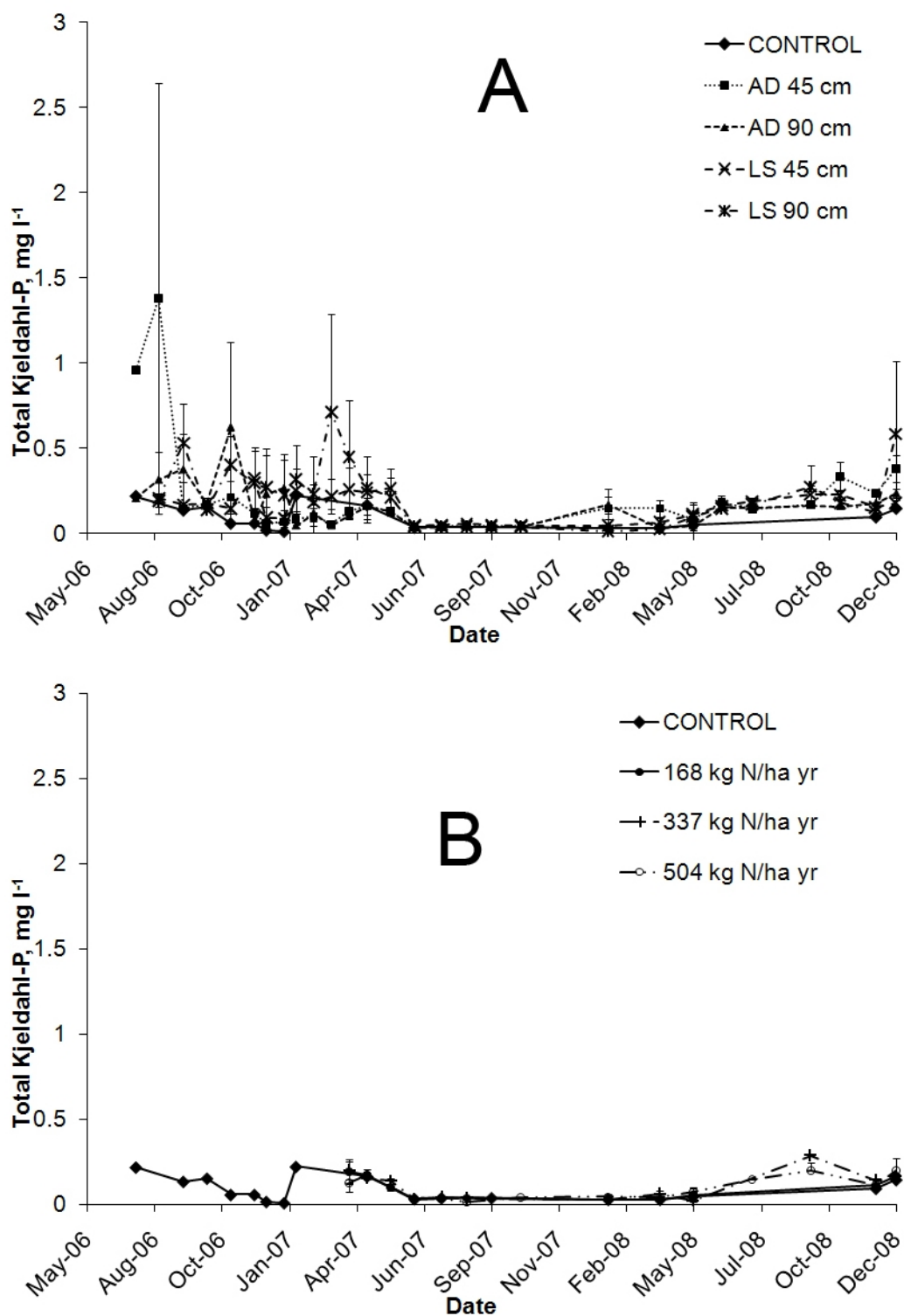


Figure 3-14. Concentrations of TKP in leachate collected by zero tension lysimeters from the DRI biosolids treatments (A) and conventional fertilizer treatments (B) through the study period (July 2006-December 2008). Bars represent standard errors.

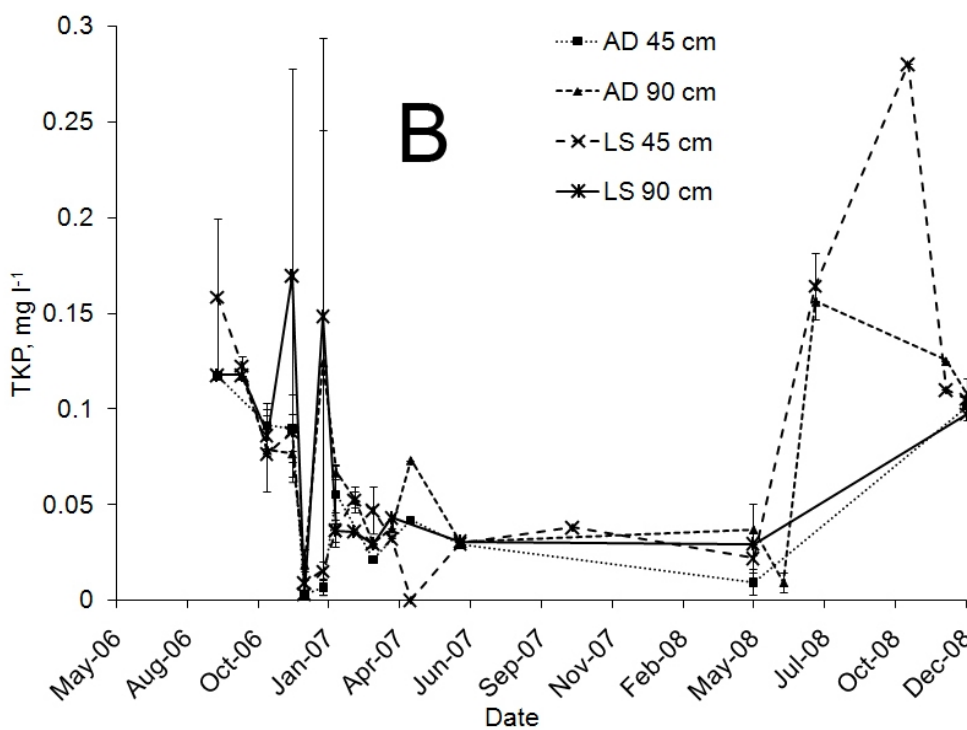
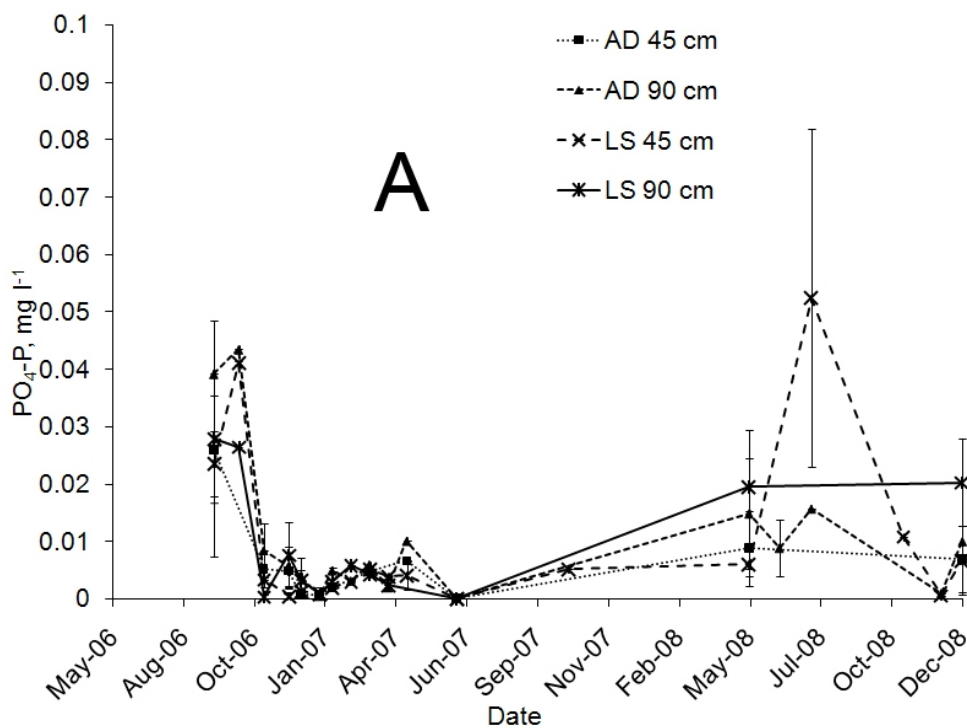


Figure 3-15. Concentrations of PO<sub>4</sub>-P (A) and TKP (B) in leachate collected by suction lysimeters from the DRI biosolids treatments through the study period (July 2006-December 2008). Bars represent standard errors.

## CHAPTER 4

### **Temporal and Spatial Changes in C, N and P in Deep Row Applied Biosolids Underlying Hybrid Poplar**

#### **ABSTRACT**

Biosolids deep row incorporation (DRI) offers an alternative recycling approach for bioenergy crop production, but nutrient additions in excess of the vegetation requirements can potentially impair water quality. The effects of DRI biosolids treated by two separate processes – anaerobic digestion and lime stabilization - on the changes in forms and mass of C, N and P were investigated in a hybrid poplar plantation in a coastal plain heavy mineral mine reclamation site to provide insight into the transformations and losses of these elements applied in the biosolids. Two treatments compared in the field experiment were: (i) anaerobically digested DRI biosolids (AD) at the rate of 426 Mg ha<sup>-1</sup>, and (ii) lime stabilized DRI biosolids (LS) at the rate of 656 Mg ha<sup>-1</sup>. We analyzed biosolids P (labile P, Al-, Fe-bound-P, Ca-bound-P, total P, Mehlich 1 P), N (total Kjeldahl N, ammonium, nitrate), and C (organic C, inorganic C) fractions, redox potential, and other physical parameters. Organic C losses were 81 Mg ha<sup>-1</sup> and 33 Mg ha<sup>-1</sup> for LS and AD biosolids, respectively. Total N lost over the course of two years was 15.2 Mg ha<sup>-1</sup> and 10.9 Mg ha<sup>-1</sup> for LS and AD biosolids, respectively, which was roughly 50% of the N applied. No significant losses of P were detected. Most of the P was Al- and Fe-bound in the AD biosolids and Ca-bound in the LS biosolids. Labile P decreased with decrease in organic C, which indicated that P leaching potential from the DRI biosolids decreased with aging. Our results

indicated that recommended rates of deep row incorporated biosolids in coarse textured soils should be based on crop N requirements and N mineralization considerations and that P mobility from biosolids of the type used should not pose a water quality risk.

## INTRODUCTION

Biosolids are often utilized as amendments for minesoils because they increase soil organic carbon, cation exchange capacity, nutrient concentrations, and promote ecosystem recovery (Ussiri and Lal, 2005). Application of biosolids to mined soils is the most economical and practical option of improving soil quality while providing a source of nutrients to the vegetation. Application of higher than agronomic biosolids rates to mineland reclamation sites is permitted by the Part 503 rule of 40 CFR (USEPA, 1993) and is widely practiced under the assumption that the reclamation benefits from such practice would be higher than possible negative environmental effects (Haering et al., 2000).

Deep row incorporation (DRI) technology is a biosolids land application method that provides a single application of nutrients sufficient for a short rotation plantation of bioenergy crops, such as hybrid poplar, and has been especially adapted for reclaiming surface mined land (Taylor et al., 1978; Kays et al., 1997; Felix et al., 2008; Felton et al., 2008). Deep row incorporation in mined land involves placement of biosolids in trenches that are immediately covered with overburden, which eliminates odor problems and maintains biosolids in an anaerobic environment. A low oxygen diffusion rate into the entrenched biosolids is expected to reduce mineralization and nitrification rates, allowing the practice to slowly transform nitrogen into plant-available forms and reducing leaching losses of nitrate (Kays et al., 1997). Thus, DRI

offers a potentially environmentally beneficial approach for utilizing high rates of biosolids to restore the productivity of surface mined soils.

Despite the popularity of this biosolids recycling method, we (Chapter 3) have shown that, within the first two years following entrenchment, DRI can result in large leaching losses of N below the biosolids seam in coarse-textured soils and produce considerable quantities of  $N_2O$  which may offset biosolids carbon sequestration gains within the first two years of entrenchment. However, the changes in the net amounts and forms of N and C retained in the DRI biosolids have never been quantified, and previous studies on the DRI biosolids (Sikora et al., 1978; Sikora et al., 1982; Kays et al., 1997; Felix et al., 2008; Felton et al., 2008) provided much speculation about the possible benefits and environmental effects of the DRI.

Phosphorus leaching was not high during the first two years of our study (Chapter 3) or in the work by Felton et al. (2008), despite the high rates of P applied with the biosolids. Phosphorus solubility and leaching potential from biosolids is normally minimized by treatment with Al and Fe salts and lime (Maguire et al., 2000; Penn and Sims, 2002; Elliott and O'Connor, 2007; Chinault and O'Connor, 2008); however, Peckenham et al. (2008) measured high P concentrations in leachate from the field-stacked biosolids. It's also not clear how the distribution of P fractions, and associated leaching potential, is affected by the change from the reductive to the oxidative conditions in the biosolids seam with time.

The objectives of our study were: (i) to determine the effects of aging on the N, C and P dynamics in the DRI biosolids seams, and (ii) to determine the changes in net masses of biosolids C, N, and P retained in the seams after two years of entrenchment.

## **MATERIALS and METHODS**

### **Site Description**

The study was conducted on a mineral sands (ilmenite and zircon) mine reclamation site in Dinwiddie County in Virginia, located 50 km south of Richmond. Slagle (Fine-loamy, siliceous, subactive, thermic, Aquic Hapludults), Myatt (Fine-loamy, siliceous, active, thermic, Typic Endoaquults) and Roanoke (Fine, mixed, semiactive, thermic, Typic Endoaquults) series originally covered the land prior to mining operations in this area. Post mining soil conditioning resulted from dewatering and sedimentation of sand and clay, physically separated during the mining process (Meredith, 2007). The resulting strongly stratified soil had two distinct particle size fractions: a coarse-textured material (sand) consisting of 96.1% 50 to 2000 $\mu\text{m}$  (sand), 2.0% 2 to 50 $\mu\text{m}$  (silt), and 1.9% <2  $\mu\text{m}$  (clay) and a finer-textured material (sandy clay loam) consisting of 50 to 2000 $\mu\text{m}$  (sand), 8.6% 2 to 50 $\mu\text{m}$  (silt), and 30.2% <2  $\mu\text{m}$  (clay) (Gee and Or, 2002). The soil at the site was mostly represented by the sand fraction which was overlaid by the 0.1-0.5 m layer of the sandy clay loam fraction. The sandy clay loam fraction was also present in fragmentary thin layers in the sand seam. The seasonal water table on the site fluctuated between 1.5 and 4 meters from the soil surface (Orndorff, personal communication).

### **Field Experimental Design**

The two treatments compared in the experiment were: one DRI biosolids rate for each of an anaerobically digested (AD) and a lime stabilized (LS) biosolids. The treatments were each replicated 4 times and arranged in a randomized complete block design. Each treatment plot was 6 m wide x 15 m long and contained two rows (trenches) for application of biosolids with a row



spacing (center-to-center) of 3 m; thus, the area of each of the 8 plots is 90 m<sup>2</sup>. The rows were also used to plant hybrid poplar.

Anaerobically digested (AD) and lime stabilized (LS) biosolids were placed in trenches excavated by backhoe at the volumetric rate of 90 cm wide×75 cm deep, which was equivalent to 2250 m<sup>3</sup> ha<sup>-1</sup>. The biosolids rates were the masses that fit in trenches. We calculated the rates of the biosolids as 426 Mg AD ha<sup>-1</sup> and 656 dry Mg LS ha<sup>-1</sup> after measuring the bulk densities of the biosolids types. The LS biosolids were obtained from Blue Plains Wastewater Treatment Plant, Washington, DC and were processed by lime stabilization ([http://www.epa.gov/owm/septic/pubs/alkaline\\_stabilization.pdf](http://www.epa.gov/owm/septic/pubs/alkaline_stabilization.pdf)). The AD biosolids were obtained from Alexandria Sanitation Authority, Alexandria, VA and were processed by anaerobic digestion (<http://epa.gov/OWM/mtb/multi-stage.pdf>). Chemical characteristics of the fresh anaerobically digested (AD<sub>f</sub>) and lime stabilized (LS<sub>f</sub>) biosolids are presented in Table 4-1. The site was established in June and July 2006, when the biosolids were entrenches and covered with fill from the trenches, and the entire area was graded to provide a soil cover of approximately 30 cm over the biosolids trenches.

Hybrid poplar (*Populus deltoides*×*nigra* ‘OP367’) stem cuttings were planted over the center of each biosolids trench at a spacing of 3 m between plants for a total of 10 trees per plot (3×3 m, 1077 trees ha<sup>-1</sup>) on March 5-6, 2007. The cuttings were purchased from Broadacres Nursery, Inc. (18335 Butteville Road N.E., Hubbard, OR 97032) and shipped refrigerated via U.S. Postal Service to Blacksburg, VA in late February. The 30 cm long cuttings were placed about 20-25 cm into the soil and protected with 30-cm tall, 5-cm diameter staked plastic tree shelters. The herbicide Roundup™ (2-(phosphonomethylamino) acetic acid) was also sprayed around the trees once each summer in 2007 and 2008 to reduce weed competition with the

poplars. Irrigation was provided during the months of May to September 2007 and June to July 2008 via overhead sprinklers to prevent poplars from succumbing to drought stress.

### **Biosolids Core Study**

We conducted analysis of biosolids sampled from one of two seams in each of the treatment replications on 27 October 2008 after 27 and 28 months of biosolids entrenchment for the LS and AD, respectively. Biosolids cores measuring 12.5 cm×12.5cm×12.5 cm were collected from the edge of the trench (0-5 cm from the side of the trench) and in the trench center (45 cm from the side of the trench) at 0-25 cm, 25-50 cm and 50-75 cm depths after exposing the seams using a backhoe to excavate and carefully brushing away soil adjacent to the biosolids. Sampling of 6 cores from each seam resulted in 24 cores for each of the aged (AD<sub>a</sub> and LS<sub>a</sub>) biosolids treatments. An additional 4 cores (soil) were collected from the 0-30 cm depth of the control plots. The biosolids seam depth was measured in order to account for shrinkage of the material due to aging effects. The cores were stored at 4<sup>0</sup>C prior to analysis. Additional cores of the fresh (AD<sub>f</sub> and LS<sub>f</sub>) biosolids, collected at the time of the biosolids entrenchment in June and July 2006 and stored in the freezer at -20<sup>0</sup>C, were thawed prior to chemical analysis.

Each of the fresh and aged AD and LS biosolids samples was analyzed for total P, Fe, Al and Ca by ICP-AES following digestion in nitric acid with hydrogen peroxide (USEPA, 1986). Bulk density of the aged biosolids cores was determined by weighing the cores and moisture content was determined by comparison of the wet and dried (65<sup>0</sup>C for 48 h) weights of the subsamples. The pH was measured in suspension of 1:2.5 (g/vol) with an Orion PerpHecT logR Benchtop meter (Thermo Scientific, Waltham, MA). The redox potential was measured by insertion of one platinum (Pt) redox electrode in the center of each biosolids core and using a

silver chloride reference electrode with single annular junction (Accumet, Fisher Scientific) with the digital multimeter DM 383 (Universal Interprises, Inc. Beaverton, OR). Wet subsamples from the biosolids cores were analyzed for  $\text{NO}_3\text{-N}$  and  $\text{NH}_4\text{-N}$  colorimetrically in a 2M KCl extraction, and TKN and TKP were determined in the Kjeldahl digests using flow injection analysis on Lachat 8000 (Lachat Instruments, Loveland, CO). Organic-N was calculated as a difference between TKN and  $\text{NH}_4\text{-N}$ . Total organic C was determined in the air dried biosolids by dry combustion on VarioMax CNS analyzer (Elementar, Mt. Laurel, NJ). Carbonates ( $\text{CO}_3^{2-}\text{-C}$ ) were calculated as the difference between organic C and total C in 0.1M HCl treated and original samples of DRI lime stabilized biosolids according to the procedure described by Hedges and Stern (1984). Determinations of bulk density, moisture content and redox potential on the fresh AD and LS biosolids were conducted by the methods described above at the time of sampling in June and July 2006, respectively.

All air dried biosolids and the soil control samples were characterized for P forms and potential P-binding constituents. Analyses included Mehlich 1 extractable P, Al, Fe and Ca, and sequentially extracted inorganic P forms (Mehlich, 1953). A sequential extraction was performed by the method of O'Connor et al. (2004) modified from (Chang et al., 1983). The extraction includes shaking of 1 g of material with 30 ml 1M KCl for 2 h on an orbital shaker, centrifuging and filtering (0.45  $\mu\text{m}$ ). The fraction represents "labile/exchangeable P." A second sequential extraction step is extraction of residual from step 1 with 30 ml 0.1M NaOH for 17h on an orbital shaker, followed by filtering (0.45  $\mu\text{m}$ ). The fraction from this step represents "Fe- and Al-bound P." A third sequential extractant, 30 ml of 0.5 M HCl, includes shaking with the residual from step 2 for 24 h and filtering (0.45  $\mu\text{m}$ ). This fraction represents "Ca-bound P." All extracted fractions were analyzed for P by ICP-AEC. The sum of KCl-P, NaOH-P and HCl-P is usually

regarded as inorganic P (Elliott et al., 2002; O'Connor et al., 2004). Organic P in the material was determined by the difference between the TKP and the inorganic P fraction.

### **Statistical Analysis**

The mean values for each DRI biosolids and soil characteristic and standard errors were calculated for every treatment and depth combination. The data was log transformed to meet the normality assumption of statistical analysis. The influence of the trench depth on the biosolids characteristics for each of the biosolids type was analyzed using a split plot design with treatment as a main plot factor and depth as a subplot factor in proc MIXED procedure (SAS Institute Inc., 2008). Differences of least squares means procedure was used to determine significant treatment effects at each depth and treatment combination. The cumulative masses of C and N forms, biosolids mass and volume, TKP and inorganic P masses were calculated using the measured bulk densities. Means and standard errors were calculated for each treatment. A Tukey multiple comparisons procedure was used to distinguish differences between the treatments in randomized complete block design using proc GLM (SAS Institute Inc., 2008). Normalized organic C (%), organic-N ( $\text{g kg}^{-1}$ ), TKN ( $\text{g kg}^{-1}$ ), moisture content (%) and bulk density ( $\text{kg m}^{-3}$ ) values from the biosolids cores were analyzed by stepwise multiple regression using proc REG procedure (SAS Institute Inc., 2008) to determine to what extent they could explain the variation in redox potential within the DRI biosolids. The fraction of organic-N remaining in the aged biosolids was regressed via forward multiple regression in proc REG (SAS Institute Inc., 2008) on the C/N ratios to determine if decrease in organic-N accompanied by mineralization is reflected by C/N ratios in the DRI biosolids. Normalized Mehlich 1 P ( $\text{g kg}^{-1}$ ) concentrations were regressed on the normalized KCl-P, NaOH-P and HCl-P fractions ( $\text{g kg}^{-1}$ )

by stepwise multiple regression using proc REG procedure (SAS Institute Inc., 2008) separately for each DRI biosolids type in order to determine Mehlich 1 P predictability for the P fractions in the DRI biosolids. The normalized KCl-P concentrations were analyzed via forward multiple regression in proc REG (SAS Institute Inc., 2008) to describe the decline of soluble/exchangeable P with decreasing organic C content (%) in the DRI biosolids.

## **RESULTS and DISCUSSION**

After two years of biosolids entrenchment, the DRI biosolids seams decreased in volume by 24-27% on average for LS<sub>a</sub> and AD<sub>a</sub>, respectively (Figure 4-1). The DRI biosolids mass significantly decreased by 77 Mg ha<sup>-1</sup>, on average, for the LS<sub>a</sub> biosolids. The decrease in total C and total N was most pronounced for the LS<sub>a</sub> and was also significant for the AD<sub>a</sub>. Lime stabilized DRI biosolids lost 81 Mg ha<sup>-1</sup> organic C and 15.2 Mg ha<sup>-1</sup> total N, which constituted 40% and 50 % of C and N original loading rates, respectively. Anaerobically digested biosolids lost 33 Mg ha<sup>-1</sup> organic C and 10.9 Mg ha<sup>-1</sup> total N, which was 25% and 48% of C and N original loading rates, respectively. In Chapter 6 we report that the hybrid poplar plantation sequestered only 3.20±0.54 Mg C ha<sup>-1</sup> and 71±12 kg N ha<sup>-1</sup> on average during the same period. There were no significant differences in the original loading rates of P and the amounts of P after two years of the biosolids entrenchment (Figure 4-2).

### **DRI Biosolids Physical Characteristics, C and N Dynamics**

Properties of AD and LS DRI biosolids were due to differences in treatment process and aging effects (Table 4-2). Depth affected all properties except organic-N, TKN, NO<sub>3</sub>-N and

carbonates (inorganic C). Table 4-1 contains the summary of the major physical properties and C and N characteristics of fresh and aged AD and LS biosolids.

The LS<sub>f</sub> biosolids had a pH of 12.5 due to treatment with lime, which likely suppressed microbial activity and decomposition rate compared to the AD<sub>f</sub> biosolids. The pH values of the DRI biosolids decreased after two years of entrenchment. The pH of AD<sub>a</sub> biosolids had decreased at the edges and in the top of the biosolids seams (i.e., 0-25, 25-50 and 50-75 cm depth at edge and 0-25 cm at center). Lime stabilized DRI biosolids had lower pH values at 0-25 cm depth and a pH of 9.4 -10.4, on average, throughout the rest of the seams. The AD<sub>f</sub> biosolids had higher moisture content and lower bulk density than the LS<sub>f</sub> biosolids. The distribution of those properties followed the similar pattern for AD<sub>a</sub> and LS<sub>a</sub> treatments. The edges of the AD<sub>a</sub> and LS<sub>a</sub> seams (including the 0-25 cm, center) were most dewatered and had significantly higher bulk density compared to the 25-50 and 50-75 cm depths in the centers of the seams. The AD<sub>a</sub> maintained higher moisture content and lower bulk density in each depth increment compared to the LS<sub>a</sub>.

The concentrations of organic C in the DRI biosolids significantly decreased from their original C levels. Organic C concentrations were not significantly different with depth in the AD<sub>a</sub> but were 25% lower than the AD<sub>f</sub>. The LS<sub>a</sub> had decreased organic C at 0-25 cm depths and at 50-75 cm depths at the edges of the seams, which contained 45% less organic C than the LS<sub>a</sub>. Organic C also decreased at 25-50 and 50-75 cm depths in the centers of the seams in the LS<sub>a</sub> treatments, which was 15% lower than LS<sub>f</sub>. Inorganic C (as carbonate) was detected at all depths of the LS<sub>a</sub> treatment. The lack of statistical difference was indirect evidence that air (CO<sub>2</sub>) could penetrate through lime stabilized biosolids seams.

The concentrations of organic-N were similar in AD<sub>f</sub> and LS<sub>f</sub> biosolids, while the concentrations of NH<sub>4</sub>-N were significantly higher in AD<sub>f</sub> than LS<sub>f</sub> (Table 4-1). The concentrations of organic-N became lower in the aged than in the fresh biosolids for both AD<sub>a</sub> and LS<sub>a</sub>. The upper part of the LS<sub>a</sub> seam and the edges also had significantly lower concentrations of organic-N compared to AD<sub>a</sub>. The concentrations of NO<sub>3</sub>-N significantly increased in AD<sub>a</sub> at all depths, and the concentrations of NH<sub>4</sub>-N increased in LS<sub>a</sub> at the 50-75 cm depth in the edges of the seams compared to the original biosolids. The concentrations of NH<sub>4</sub>-N significantly decreased in the AD<sub>a</sub> treatment at all depths except the 50-75 cm in the center of the seam, as compared to the original biosolids. The NO<sub>3</sub>-N concentrations were also significantly higher in the AD<sub>a</sub> than in the LS<sub>a</sub> treatments, while LS<sub>a</sub> had higher concentrations of NH<sub>4</sub>-N than AD<sub>a</sub>. The differences in NH<sub>4</sub>-N concentrations between the two aged biosolids types resulted in minimal differences in TKN (comprised by NH<sub>4</sub>-N and organic-N) concentrations among AD<sub>a</sub> and LS<sub>a</sub>. The C/N ratios were mostly similar to those in original biosolids, except for 25-50 cm depth in the center of LS<sub>a</sub>, which was higher than LS<sub>f</sub>. This is likely because the centers of LS<sub>a</sub> were least affected by decomposition and tended to have higher C levels than the rest of the seam.

The fraction of organic N lost from the DRI biosolids seams was calculated by subtracting the concentration of organic-N remaining from the organic-N in the original biosolids and dividing it by the organic-N in the original biosolids. That fraction was used as an approximate estimate for the amount of N mineralized. It is important to note that the lost organic-N fraction slightly overestimated the actual N mineralization rates due to the loss of a portion of organic-N via leaching from the biosolids seams (Chapter 3). The percentage of organic-N lost via leaching was approximately 1% of the entire N loss. The fraction of organic-N

lost from the biosolids regressed on C/N ratios for AD<sub>a</sub> and LS<sub>a</sub> resulted in significant fit (Figure 3). Higher C/N ratios resulted from N mineralization and loss of organic-N at more rapid rate than C loss. Previous research showed that N mineralization in the biosolids can be related (Gilmour and Skinner, 1999; Parnaudeau et al., 2004) or not related (Parnaudeau et al., 2009) to C/N ratios. The total loss of organic-N in the DRI biosolids was 41% and 58% for AD<sub>a</sub> and LS<sub>a</sub>, respectively. These values indicate that N mineralization of the DRI biosolids in our study was 40% lower in the AD<sub>a</sub> compared to LS<sub>a</sub>. Mineralization of N during 2 years after entrenchment was also comparable with the first-year N mineralization level of 40% in land applied biosolids reported by Gilmour et al. (2003).

The LS<sub>f</sub> biosolids had significantly lower redox potential than the AD<sub>f</sub> biosolids. After two years of entrenchment the Eh for AD<sub>a</sub> indicated aerobic conditions everywhere within the seam except the 25-50 cm in the center with Eh of 219±24mV, which is the lower level for nitrification (Table 4-1). The LS<sub>a</sub> treatment had redox potentials as low as 24±35mV within the 25-50 and 50-75 cm depths of the seams, which would be expected to maintain Fe as Fe(II) (Masscheleyn et al., 1990). Stepwise multiple regression was performed to identify the factors (organic C, organic N, TKN, NH<sub>4</sub>-N, NO<sub>3</sub>-N, moisture content (Θ), bulk density) that explain the variation of redox potential, Eh, with aging in the DRI biosolids for each biosolids type. The NO<sub>3</sub>-N concentration and the moisture content (Θ) were the best predictors for Eh in the anaerobically digested AD<sub>a</sub> and AD<sub>f</sub> biosolids by the relationship:  $Eh = 111(\pm 35) + 48(\pm 3) \times \ln NO_3 - N - 309(\pm 61) \times \theta^2$  [ $P < 0.05$   $R^2 = 0.95$ ]. Increasing concentrations of NO<sub>3</sub>-N and decreasing moisture content were associated with increasing redox potentials in the anaerobically digested DRI biosolids. That was an indication that N mineralization and nitrification resulting in NO<sub>3</sub>-N increase, as well as dewatering of the biosolids favored aerobic conditions. Organic C



best predicted the Eh in the LS<sub>a</sub> and LS<sub>f</sub> biosolids according to the following equation:  $Eh = 292(\pm 50) - 0.20(\pm 0.05) \times \text{organic C}^2$  [ $P < 0.05, R^2 = 0.30$ ]. Decreasing organic C concentrations resulted in increased redox potentials in the seams of the lime stabilized biosolids. Redox potentials of +300 mV and +250mV are at the upper boundaries of CH<sub>4</sub> emissions and denitrification in the forest soils (Yu et al., 2006); therefore, significant greenhouse gas production from the DRI biosolids is expected (Chapter 5).

Lime stabilized biosolids resulted in the highest losses of organic C, possibly as a result of their increased labile organic matter susceptible to mineralization or leaching (Curtin et al., 1998). We did not measure absolute carbon losses from the DRI biosolids, but increased CH<sub>4</sub> and CO<sub>2</sub> emissions were detected in spring 2009 from the LS<sub>a</sub> (Chapter 5). This was possibly a result of high amounts of labile organic matter from the DRI biosolids present in the soil surrounding the seams.

High losses of N from the DRI biosolids were a result of N mineralization that occurred within the biosolids seams during the two years of entrenchment. Significant losses of NO<sub>3</sub>-N and NH<sub>4</sub>-N in the biosolids seams (Figure 4-1), particularly in the AD<sub>a</sub>, and increased redox potentials were indicative of mineralization and nitrification in the seams. Previous research demonstrated high leaching concentrations of NH<sub>4</sub>-N (Felton et al., 2008), NO<sub>3</sub>-N and organic-N (Chapter 3) from the DRI biosolids. Leachate from stockpiled biosolids can also contain high TKN concentrations (Peckenham et al., 2008). This suggests that dissolved organic N can leach to adjacent soil, where pH and Eh conditions promote mineralization and nitrification, and pose groundwater quality risk (Sikora et al., 1978; van Kessel et al., 2009).

We (Chapter 5) also measured high N<sub>2</sub>O emissions from the biosolids seams. Losses of N, however, were not accounted for entirely by leaching and N<sub>2</sub>O emissions. Combined N

leaching and emissions of  $N_2O$  accounted for only 6.4% of the N lost from the  $LS_a$  and 10.8% of the N lost from the  $AD_a$ , as calculated from our seam analyses. Some of the unaccounted N loss may have occurred via lateral flow, which we weren't able to quantify with zero tension lysimeters (Chapter 3). Dinitrogen gas may also have been one of the denitrification products (Chapter 5), but we did not measure  $N_2$ . We also expect some N loss via ammonia volatilization, which was shown to remove up to 50% of total N from landfill bioreactors (Berge et al., 2005).

### **Transformations of the DRI Biosolids Phosphorus**

We found significant treatment by depth interactions for KCl and NaOH extractable P, TKP, organic P and Mehlich 1 P, and significant treatment and depth effects for HCl extractable P. (Table 4-2). Inorganic P concentrations in the seams did not vary with depth. Table 4-3 provides the concentrations, distributions within seams, and means separations among treatments for biosolids P forms and Mehlich 1 extractable Al, Fe and Ca. The two biosolids used in the study differed in their amounts of TKP, which were three times higher in the  $AD_f$  than in the  $LS_f$ . The  $LS_f$  biosolids had the highest amounts of total Ca and highest Ca/P ratio due to their treatment processing (Table 4-4). The  $AD_f$  had higher concentrations of Al and Fe than the  $LS_f$  biosolids. This resulted in most of the P complexed in Al and Fe forms (NaOH extractable) in the  $AD_a$ . Calcium-associated (HCl extractable) P dominated in the  $LS_a$  biosolids. Our results were consistent with previous research which demonstrated that lime stabilized biosolids P is mostly present as crystalline hydroxylapatite and beta-tricalcium phosphate, and P forms in anaerobically digested biosolids are predominantly complexed with Al and Fe oxides (Shober et al., 2006; Ajiboye et al., 2007).

Labile P levels estimated in the first step (KCl) of sequential extraction procedure were significantly lower in the aged than fresh biosolids. Lime stabilized DRI biosolids varied in KCl-P from 0.08 to 0.14 g kg<sup>-1</sup>, with significantly higher concentrations at the 25-50 and 50-75 cm depths than the KCl-P levels in the rest of the biosolids seams. Anaerobically digested DRI biosolids had significantly lower amounts of KCl-P than LS<sub>a</sub>, and the labile P levels were similar at all depths. Labile P, which was previously shown to reflect potentially leachable P (Elliott et al., 2002), decreased 4-5 times in the DRI biosolids compared to the original material, and was within the lower range compared to the biosolids in the study by O'Connor et al. (2004).

Labile KCl-P concentrations were comparatively high in the parts of the biosolids seams (and in fresh biosolids) which were under reducing conditions and Eh range of 24-61 mV for LS<sub>a</sub> and -43 and -123 mV for AD<sub>f</sub> and LS<sub>f</sub>, respectively, while the KCl-P in the oxic conditions in the AD<sub>a</sub> and at 0-25 cm depth in the LS<sub>a</sub> were lower than in LS<sub>a</sub>, AD<sub>f</sub> and LS<sub>f</sub> biosolids. This contradicts to the results of Shober and Sims (2009) who did not observe increased dissolved P concentrations of biosolids-amended soil under anoxic compared to oxic conditions. Change from reduced to oxidized conditions results in conversion of amorphous Fe(II) forms into Fe(III) hydroxides, which occurs at redox potentials higher than +50-100 mV (Masscheleyn et al., 1990). Oxidation of Fe (II) to Fe (III) was likely to occur during the mineralization of the DRI biosolids seams, resulting in desorption of P from Fe (II) surfaces and leaching into the lower parts of the biosolids seams.

The TKP concentrations in the LS<sub>a</sub> treatment were significantly higher at the 50-75 cm depth at the edge of the seam than in the LS<sub>f</sub> and the 0-25 cm of the LS<sub>a</sub> seams. The TKP was also significantly lower at the 0-25 cm and 25-50 cm depths in the centers of the LS<sub>a</sub> than LS<sub>f</sub>. This was an indication of vertical P transport in the LS DRI biosolids. Therefore, enrichment of

the lower parts of the  $LS_a$  with TKP could explain higher concentrations of KCl-P due to relative depletion of P adsorption sites. KCl-P values regressed on organic C content for both DRI biosolids types resulted in significant fits (Figure 4-4). This indicates that KCl-P concentrations were increased at high organic C levels, a dependence also observed by Dell'Olio et al. (2008), who found an exponential relationship between increase in water soluble P and organic matter content in organic soils. Increase in organic matter was previously related to increase in labile P concentrations (Afif et al., 1995; Mukherjee et al., 2009; Uygur and Karabatak, 2009), likely due to organic matter occupation of P sorption sites (McDowell and Sharpley, 2001). This also suggests that biosolids aging decreases P solubility, as KCl-P decreased with decrease in organic C.

Inorganic P was the largest portion of the biosolids P, and constituted 70% (on average) for both  $AD_f$  and  $LS_f$  biosolids (Figure 2). Inorganic P was mostly contained in Fe and Al forms (NaOH extractable) for the  $AD_a$  and mostly Ca and Mg associated in the  $LS_a$ , which is consistent with previous research (Penn and Sims, 2002; O'Connor et al., 2004; Shober et al., 2006). Despite the uniformity of the NaOH-P and HCl-P fractions with depth in the  $AD_a$  and  $LS_a$  seams, respectively, significantly lower concentrations of Al and Fe associated-P were detected at the 25-50 and 50-75 cm depths of the  $LS_a$  than in the  $LS_f$ .

Organic P fractions were uniformly distributed with depth in the  $AD_a$  treatment; however, they were lower in the 0-25 cm depth of the  $LS_a$  than in the  $LS_f$  biosolids and the lower parts of the  $LS_a$  seam. This was possibly a result of increased mineralization of organic matter in the upper part of lime stabilized DRI biosolids seams, as well as colloiddally-facilitated transport of organic P to the lower parts of the  $LS_a$  seam. Previous research has shown dominance of Al- and Fe-P fractions despite repeated applications of lime stabilized biosolids to soils (Maguire et al.,

2000). Calcium associated P was also shown to transform into more labile forms (Sui et al., 1999), which precipitate with Al and Fe oxyhydroxides in the low pH aerobic conditions (Shober et al., 2006). This wasn't the case in the in LS<sub>a</sub> treatment, as we observed a decrease in the Al- and Fe-associated P fractions with aging, and accumulation of organic P fraction in the 50-75 cm depth of the LS<sub>a</sub> seam.

Mehlich 1 extractable Al and Fe were higher and Mehlich 1 Ca lower in the AD<sub>a</sub> than in the LS<sub>a</sub> treatment. No relationship was observed between Mehlich 1 Al, Fe and Ca and the KCl-P, NaOH-P and HCl-P fractions, as determined by multiple linear regression (data not shown), which was possibly a result of organic matter competing for exchange sites with P (Mukherjee et al., 2009) and some of the Mehlich 1 Al, Fe and Ca associated with organic matter rather than P.

Mehlich 1 P was regressed separately for each DRI biosolids type on the inorganic P fractions (KCl-P, NaOH-P, HCl-P and the sum of the inorganic P fractions) via stepwise multiple regression. Labile KCl-P was the best predictor of Mehlich 1 P for LS<sub>a</sub> treatment (Figure 4-4). Decreasing KCl-P concentrations resulted in decreased Mehlich 1 P concentrations in the lime stabilized DRI biosolids seams. No inorganic P fractions were associated with Mehlich 1 P in the anaerobically digested DRI biosolids and the Mehlich 1 P for AD<sub>a</sub> was 1.57 g P kg<sup>-1</sup> on average. This indicated that unlike KCl-P, Mehlich 1 P might not be a good predictor of P leaching from the DRI biosolids, as P mass balance in the current study (Figure 4-2) and results from our leaching study (Chapter 3) showed essentially no P loss from the AD<sub>a</sub> and LS<sub>a</sub> biosolids seams while Mehlich 1 P values were high in the AD<sub>a</sub> treatment. Our data on Mehlich 1 P in AD<sub>a</sub> was contradictory to the previous studies (Sallade and Sims, 1997; Maguire and Sims, 2002) that indicated relation between labile P and Mehlich 1 P.

## CONCLUSIONS

Our results demonstrated that the DRI biosolids in the coarse-textured soils underwent significant decomposition of organic matter and N mineralization and nitrification after two years of entrenchment, which resulted in prominent pH decrease and compaction in the edges of the biosolids seams. Redox conditions within the biosolids seams changed towards oxidative, and were higher in the upper parts of the seams, indicating that anaerobic processes such as denitrification were likely favored at the bottoms of the seams.

Organic matter decomposition in the AD biosolids occurred at the same rate throughout the seams, while LS biosolids seams were more decomposed in the upper part and in the edges of the seams. Organic C level decreased by 40% in the LS biosolids seams compared to 25% in the AD seams, likely due to increase in labile organic matter susceptible to mineralization in the alkaline LS biosolids, similar to other studies.

Both AD and LS biosolids seams lost about 50% of total N over the course of 2 years. Concentrations of  $\text{NO}_3\text{-N}$  were higher in the AD, while  $\text{NH}_4\text{-N}$  was higher in the LS biosolids seams. Close to 90% of N lost from the DRI biosolids seams was either lost to denitrification as  $\text{N}_2$ , ammonia volatilization, or leached into groundwater unaccounted by zero tension lysimeters (Chapter 3).

Most of the AD biosolids P was complexed in Al and Fe forms, and P in the LS seams was Ca-associated. We did not detect significant P losses from the DRI biosolids; however, there was significant translocation of P towards the lower parts of the lime stabilized DRI biosolids seams. This was attributed to the colloiddally-facilitated transport of organic P and mineralization of the upper parts of the LS seams. Mehlich 1 P test of the DRI biosolids was not useful for predicting labile P concentrations, which are related to P concentrations in leachate. Labile P

decreased with decrease in organic C in the AD and LS biosolids seams, which indicated that P leaching potential from the DRI biosolids decreased with aging.

The results of our study represent the effects of C, N and P transformations in the DRI biosolids applied to coarse-textured soils. Our data showed that anaerobic conditions were not prevalent enough within the biosolids seams to maintain the low N mineralization and nitrification and C decomposition rates needed to prevent N and C loss. Our results indicated biosolids rate for environmentally sound deep row incorporation in coarse textured soils should be based on crop N requirements and N mineralization considerations. There was no evidence that the DRI biosolids treated with Al and Fe salts or lime will result in P loss. However, more research is needed to assess the C and N transformations in the conditions of restricted access to oxygen (e.g., fine-textured soils).

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## TABLES

Table 4-1. Physical properties and C and N characterization of soil, fresh biosolids, and the DRI biosolids after two years of entrenchment.

Treatment <sup>a</sup>	Core depth, cm	pH <sup>b</sup>	Eh	Moisture content, %	$\rho_b$ , kg m <sup>3</sup>	Organic C, %	Inorganic C, %	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	Organic-N	C/N
									-----g kg <sup>-1</sup> -----			
AD <sub>f</sub>	-	8.1(±0) cd	-43(±17) e	71.0(±0.4) a	190±0 e	30.7(±0) ab	0	0 d	9.95(±0.02) ab	53.06(±0.31) a	43.10(±0.30) a	5.8(±0) c
AD <sub>a</sub> (edge)	0-25	4.8(±0.1) f	331(±8) ab	50.3(±2.1) d	320±20 bc	22.9(±0.5) d	0	0.60(±0.15) a	0.13(±0.05) e	23.71(±1.09) bc	23.57(±1.08) b	9.5(±0.5) abc
	25-50	4.7(±0.1) f	319(±15) ab	57.5(±1.5) d	270±10 cd	23.5(±0.4) d	0	0.64(±0.07) a	0.13(±0.03) e	25.91(±1.71) bc	25.78(±1.70) b	8.9(±0.6) abc
	50-75	5.1(±0.3) f	314(±12) abc	65.4(±1.7) abc	240±20 de	23.1(±0.8) d	0	0.85(±0.11) a	0.13(±0.03) e	27.77(±2.29) bc	27.64(±2.28) b	8.2(±0.5) abc
AD <sub>a</sub> (center)	0-25	5.0(±0.3) f	316(±20) ab	57.3(±3.0) d	270±10 cd	21.3(±1.6) de	0	0.73(±0.17) a	0.42(±0.03) de	27.57(±1.80) bc	27.14(±1.78) bc	7.7(±1.0) bc
	25-50	6.7(±0.4) de	219(±24) c	72.5(±1.2) a	180±10 e	23.7(±0.5) d	0	0.50(±0.19) ab	3.44(±1.20) cd	31.33(±2.33) b	27.89(±3.43) b	7.6(±0.7) bc
	50-75	6.3(±0.7) e	245(±37) bc	67.7(±3.8) ab	230±10 de	25.0(±0.6) cd	0	0.52(±0.19) a	4.72(±1.63) ab	31.34(±3.99) b	26.62(±4.12) bc	8.3(±1.2) abc
LS <sub>f</sub>	-	12.5(±0) a	-123(±9) f	64.7(±0.6) bc	280±0 cd	33.0(±0) a	0	0.03(±0) c	0.85(±0.01) d	44.38(±0.26) a	43.54(±0.26) a	7.4(±0.1) bc
LS <sub>a</sub> (edge)	0-25	7.6(±0.1) d	162(±6) c	54.8(±4.0) d	310±10 bc	17.2(±1.6) e	3.8(±1.3) a	0.15(±0.11) bc	1.56(±1.03) d	20.21(±1.37) c	18.64(±0.73) cd	8.6(±1.2) abc
	25-50	9.4(±0.9) bc	61(±52) d	63.1(±1.3) bcd	330±10 bc	26.6(±1.6) c	2.3(±1.1) a	0.10(±0.05) c	2.96(±0.77) bcd	25.46(±2.08) bc	22.51(±2.22) bc	10.6(±0.9) ab
	50-75	9.4(±0.9) bc	61(±50) d	61.1(±3.4) cd	390±30 b	18.1(±2.3) e	1.9(±1.9) a	0.09(±0.05) c	5.65(±1.47) bc	22.41(±5.01) c	16.76(±4.50) d	9.3(±2.6) abc
LS <sub>a</sub> (center)	0-25	7.6(±0.1) d	159(±5) c	55.9(±4.9) d	350±20 bc	22.2(±2.7) d	3.5(±0.3) a	0.02(±0.02) d	3.34(±1.22) cd	21.22(±2.31) c	17.88(±1.62) d	10.7(±1.4) ab
	25-50	10.4(±0.8) b	48(±51) d	64.7(±0.8) bc	310±10 bc	26.8(±1.8) c	2.7(±1.0) a	0.06(±0.03) c	2.29(±0.45) cd	25.10±5.82 bc	22.80(±5.44) bcd	12.1(±2.1) a
	50-75	10.1(±0.6) b	24(±35) de	65.2(±0.9) bc	350±20 bc	29.2(±1.6) b	1.2(±0.7) a	0.10(±0.03) b	2.02(±0.47) cd	27.96±5.63 bc	25.95(±5.74) bc	11.5(±2.0) ab

<sup>a</sup> Fresh anaerobically digested (AD<sub>f</sub>) and lime stabilized (LS<sub>f</sub>) biosolids, and the DRI anaerobically digested (AD<sub>a</sub>) and lime stabilized (LS<sub>a</sub>) biosolids from the seams after two years from incorporation in October 2008.

<sup>b</sup> Means with SEs followed by the same letter in each column are not significantly ( $P < 0.05$ ) different.

Table 4-2. Effects of the biosolids stabilization treatment and the core depth on the physical properties, C and N forms, P characterization, and Mehlich 1 extractable P, Al, Fe and Ca

Response Variable	p-values		
	Treatment	Depth	Treatment×Depth
pH	<0.0001	<0.0001	0.1034
Eh	<0.0001	0.0006	0.1756
Moisture content	<0.0001	<0.0001	0.0416
$\rho_b$	0.0036	0.0488	0.0283
Organic C	<0.0001	<0.0001	<0.0001
Inorganic C	-	0.3808	-
NO <sub>3</sub> -N	<0.0001	0.2279	0.1376
NH <sub>4</sub> -N	<0.0001	0.0006	0.0010
TKN	<0.0001	0.2723	0.8461
Organic-N	<0.0001	0.5323	0.3602
C/N	0.0108	0.8876	0.3584
KCl P	<0.0001	0.0002	0.0005
NaOH P	<0.0001	0.0108	0.0244
HCl P	<0.0001	0.0381	0.0887
Inorganic P	<0.0001	0.2164	0.3839
TKP	<0.0001	0.0016	<0.0001
Organic P	<0.0001	0.0069	<0.0001
Mehlich1 P	<0.0001	0.0002	0.0009
Mehlich 1 Al	<0.0001	0.0085	0.0062
Mehlich 1 Fe	<0.0001	0.0218	0.0214
Mehlich 1 Ca	<0.0001	0.0004	0.5644

Analysis conducted as a split-plot design in proc MIXED procedure in SAS. All response variables are log transformed.

Table 4-3. Phosphorus characterization and selected properties of soil, fresh biosolids, and the DRI biosolids after two years of entrenchment.

Treatment <sup>d</sup>	Core depth, cm	Sequentially extracted P				TKP	Organic P	Mehlich 1			
		KCl <sup>b</sup>	NaOH	HCl	Sum			P	Al	Fe	Ca
-----g kg <sup>-1</sup> -----											
AD <sub>f</sub>	-	0.12(±0) bcd	12.98(±0.08) a	4.15(±0.09) bc	17.24(±0.17) a	27.57(±1.03) ab	10.33(±1.14) a	1.94(±0.02) a	2.36(±0.01) b	7.14(±0.03) a	19.23(±0.03) c
AD <sub>a</sub> (edge)	0-25	0.02(±0) f	15.88(±1.79) a	3.05(±0.13) d	18.95(±1.73) a	24.19(±0.48) abc	5.24(±1.52) abc	1.57(±0.09) abc	4.50(±0.26) ab	2.36(±0.06) b	11.88(±2.39) de
	25-50	0.02(±0) f	17.57(±0.37) a	3.07(±0.16) d	20.66(±0.51) a	26.80(±0.72) ab	6.14(±0.66) bc	1.64(±0.12) ab	4.89(±0.15) ab	2.06(±0.20) b	13.13(±0.41) de
	50-75	0.02(±0) f	16.38(±0.56) a	3.40(±0.44) d	19.80(±0.72) a	28.27(±3.09) ab	8.46(±3.04) a	1.37(±0.21) bc	4.29(±0.43) ab	1.66(±0.36) b	15.64(±3.30) d
AD <sub>a</sub> (center)	0-25	0.02(±0) f	15.63(±1.47) a	2.62(±0.36) d	18.27(±1.81) a	25.80(±2.00) abc	7.52(±2.51) ab	1.69(±0.07) ab	4.33(±0.13) ab	2.12(±0.17) b	11.01(±2.06) e
	25-50	0.03(±0) f	13.63(±0.74) a	4.81(±0.37) abc	18.47(±0.63) a	29.89(±2.61) a	11.42(±2.67) a	1.49(±0.15) a	4.00(±0.07) ab	2.10(±0.25) b	17.73(±0.44) cd
	50-75	0.02(±0) f	13.88(±1.35) a	3.99(±0.94) d	17.89(±1.74) a	21.72(±3.55) bc	3.82(±2.11) bc	1.66(±0.19) abc	4.47(±0.35) ab	2.49(±0.75) b	16.29(±0.84) cd
LS <sub>f</sub>	-	0.60(±0.03) a	0.44(±0) b	5.05(±0.04) ab	6.09(±0.06) bc	8.65(±0.04) de	2.56(±0.06) abc	1.14(±0.01) c	0.03(±0) c	0.05(±0) f	66.28(±1.36) ab
LS <sub>a</sub> (edge)	0-25	0.07(±0.01) e	0.44(±0.07) b	5.78(±0.41) a	6.29(±0.42) b	6.36(±0.41) ef	0.07(±0.01) d	0.10(±0.02) fg	0.003(±0) f	0.11(±0.03) d	49.77(±2.44) b
	25-50	0.14(±0.02) b	0.27(±0.04) c	5.96(±0.39) a	6.37(±0.40) b	7.95(±1.41) def	1.58(±1.08) c	0.27(±0.06) e	0.003(±0) de	0.12(±0.03) d	60.05(±1.97) ab
	50-75	0.11(±0.02) bcd	0.18(±0.04) d	4.59(±0.84) abcd	4.88(±0.90) cd	11.64(±3.38) d	6.76(±3.30) ab	0.25(±0.07) ef	0.002(±0) de	0.12(±0.04) d	56.64(±1.97) ab
LS <sub>a</sub> (center)	0-25	0.08(±0.02) de	0.27(±0.07) c	4.43(±0.75) bcd	4.78(±0.82) d	5.90(±0.49) f	1.12(±0.48) c	0.73(±0.32) d	0.01(±0.005) d	0.49(±0.26) c	53.14(±5.21) ab
	25-50	0.16(±0.03) b	0.20(±0.02) cd	4.87(±0.49) abcd	5.23(±0.50) bcd	6.51(±1.34) f	1.28(±1.13) cd	0.26(±0.03) e	0.004(±0) de	0.07(±0) d	65.44(±1.46) a
	50-75	0.17(±0.03) b	0.24(±0.04) cd	5.79(±0.11) ab	6.20(±0.10) bc	19.06(±2.07) c	12.86(±2.01) a	0.50(±0.21) de	0.003(±0) de	0.08(±0.01) df	65.43(±2.99) ab

<sup>a</sup> Fresh anaerobically digested (AD<sub>f</sub>) and lime stabilized (LS<sub>f</sub>) biosolids, and the DRI anaerobically digested (AD<sub>a</sub>) and lime stabilized (LS<sub>a</sub>) biosolids from the seams after two years from incorporation in October 2008.

<sup>b</sup> Means with SEs followed by the same letter in each column are not significantly (P<0.05) different.

Table 4-4. Concentrations of total P, Ca, Fe and Al in fresh anaerobically digested (ADf) and lime stabilized (LSf) biosolids and the molar ratios of the total Ca/P and (Fe+Al)/P.

Biosolids	Value for characteristic					
	P	Ca	Fe	Al	Ca/P	(Fe+Al)/P
	-----g kg <sup>-1</sup> -----				-----mol mol <sup>-1</sup> -----	
ADf	26.5	23.5	43.0	24.7	0.69	1.97
LSf	8.7	114.5	34.3	3.9	10.20	2.70

## FIGURES

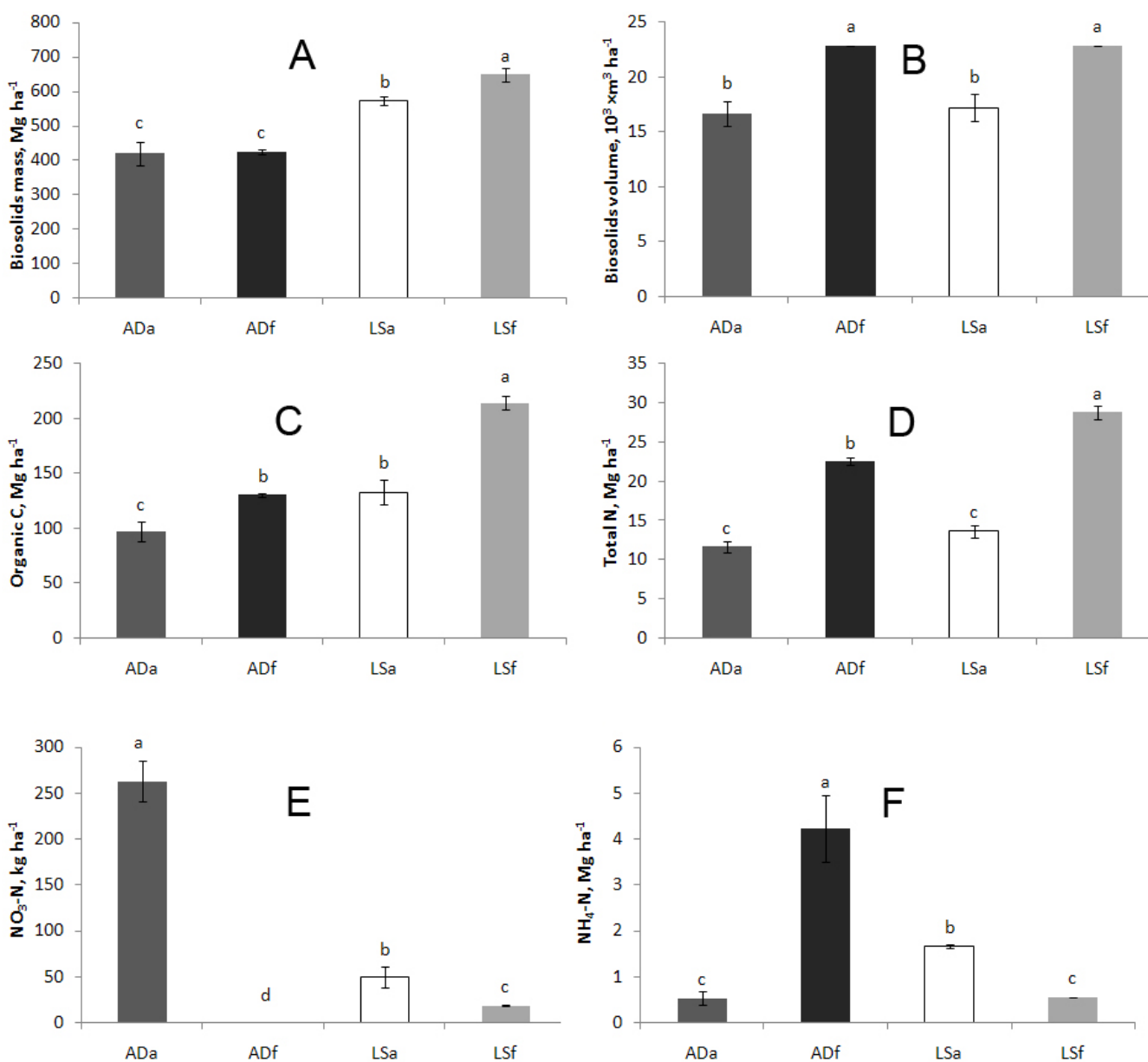


Figure 4-1. Characteristics of the fresh applied DRI anaerobically digested (AD<sub>f</sub>) and lime stabilized (LS<sub>f</sub>) biosolids and aged DRI biosolids two years after entrenchment (AD<sub>a</sub> and LS<sub>a</sub>): biosolids mass loadings (A); changes in DRI biosolids seams volume (B); organic C content (C); Total N (D) NO<sub>3</sub>-N (E) and NH<sub>4</sub>-N (F) dynamics. Error bars represent SEs. Columns in each graph followed by the same letter are not significantly different (P>0.05).



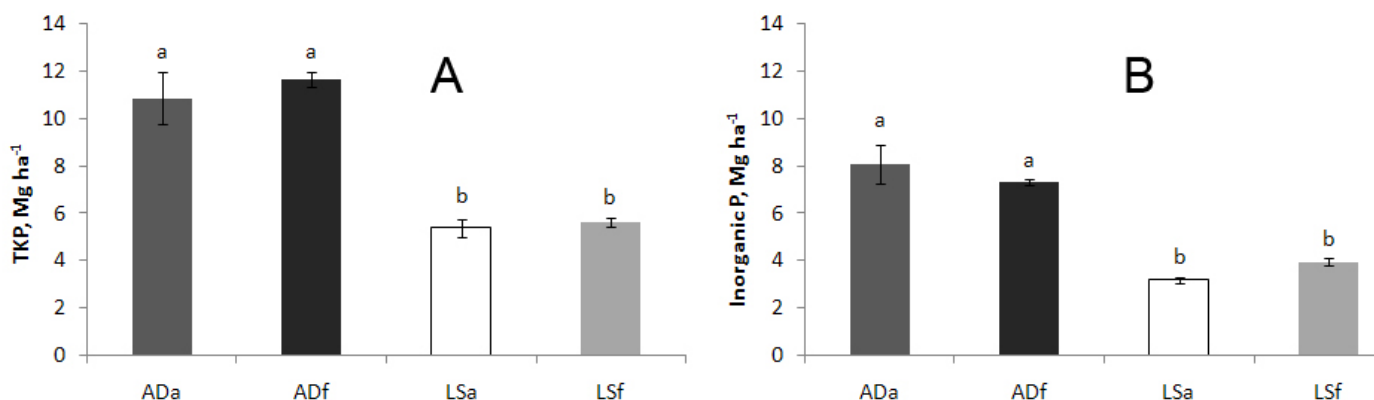


Figure 4-2. Loading rates of Total Kjeldahl P (A) and inorganic P (B) in the fresh applied DRI anaerobically digested (AD<sub>f</sub>) and lime stabilized (LS<sub>f</sub>) biosolids and aged DRI biosolids two years after entrenchment (AD<sub>a</sub> and LS<sub>a</sub>). Error bars represent SEs. Columns in each graph followed by the same letter are not significantly different ( $P > 0.05$ ).

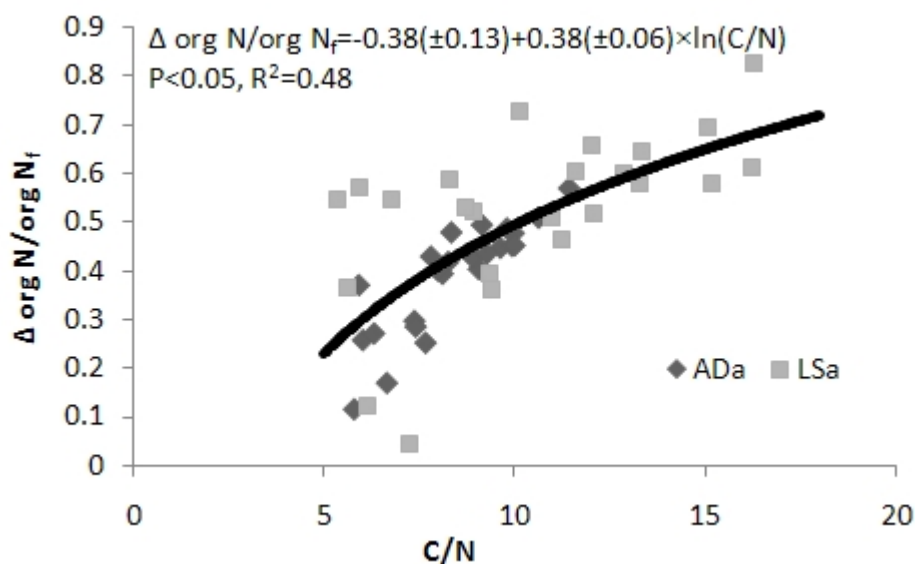


Figure 4-3. Relationship between the organic N lost to organic N in the fresh biosolids ( $\Delta \text{org N}/\text{org N}_f$ ) expressed as a decimal fraction and C/N ratios in the DRI biosolids after two years of entrenchment.

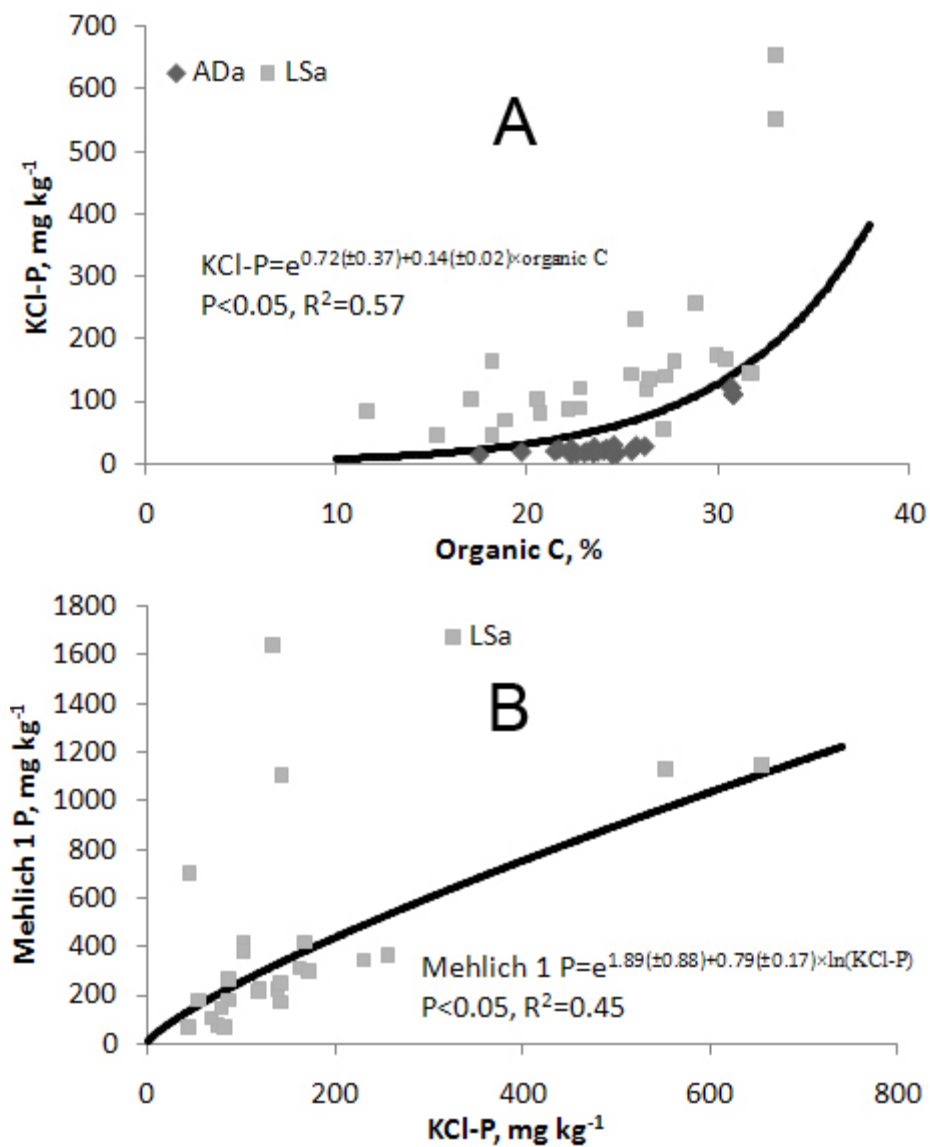


Figure 4-4. Relationships between KCl extractable P and organic C for the anaerobically digested (AD<sub>a</sub>) and lime stabilized (LS<sub>a</sub>) DRI biosolids (A), and Mehlich 1 P and KCl extractable P for LS<sub>a</sub> treatment (B). Lines are shown as predicted by linear regression equations in each graph.

## CHAPTER 5

### **Greenhouse Gas Emissions from Deep Row Applied Biosolids in Hybrid Poplar Plantation**

#### **ABSTRACT**

The effects of deep row incorporated (DRI) biosolids and conventional N fertilizer on N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> emissions were investigated in a hybrid poplar plantation in a Coastal Plain sand mine reclamation site. Four treatments compared in the field experiment were: (i) anaerobically digested (AD) DRI biosolids at the rate of 426 Mg ha<sup>-1</sup>, (ii) lime stabilized (LS) DRI biosolids at the rate of 656 Mg ha<sup>-1</sup>, (iii) conventional fertilizer at the rate of 504 kg N ha<sup>-1</sup> yr<sup>-1</sup>, and (iv) conventional fertilizer at the rate of 0 kg N ha<sup>-1</sup> yr<sup>-1</sup>. Nitrous oxide emission data were fitted to a modified sine emission dynamics model, and estimated cumulative emissions were compared. In the laboratory experiment, intact cores were collected from the DRI biosolids trenches and incubated for 2 hours. Contributions from CH<sub>4</sub> and CO<sub>2</sub> emissions to the radiative forcing were very small compared to N<sub>2</sub>O. Greenhouse gases were produced at all depths of the AD seams and only in the 0-25 cm depth of the LS seams. More N<sub>2</sub>O was produced in the DRI biosolids treatments than in the conventional fertilizer treatments, which produced similar amounts, and N<sub>2</sub>O production was higher in AD than in LS treatments. Nitrous oxide emissions peaked during summer at 34.8±4.0 mg N<sub>2</sub>O m<sup>-2</sup> h<sup>-1</sup> and at 12.1±1.7 mg N<sub>2</sub>O m<sup>-2</sup> h<sup>-1</sup> for AD and LS treatments, respectively. Expressed as global warming potentials for the period of October 2006 to December 2008, N<sub>2</sub>O emissions from AD treatments were 4.6 times higher than from LS and

14.5-16.1 times higher than from the fertilizer treatments, and were equivalent to 101.5 Mg C ha<sup>-1</sup>. Our results indicated that deep row incorporation of LS biosolids may pose a lower risk of high N<sub>2</sub>O emissions leading to reduction of C sequestration benefits from the DRI biosolids in coarse textured soils compared to AD biosolids.

## INTRODUCTION

Nitrous oxide (N<sub>2</sub>O), methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>) are greenhouse gases (GHG) important in radiative forcing and contributing to the global warming effect in the atmosphere. The atmospheric lifetimes of CH<sub>4</sub> and N<sub>2</sub>O are 12 and 114 years, and their global warming potentials are 25x and 298x CO<sub>2</sub>, respectively, during a 100 year time horizon (IPCC, 2007).

Previous studies have shown that GHG emissions increase following application of organic amendments to soils (Christensen, 1983; Barton and Schipper, 2001; Velthof et al., 2002; Jones et al., 2005; Paramasivam et al., 2008). The magnitude of increase in GHG emissions was demonstrated to be larger (Christensen, 1983; Jones et al., 2005) or similar (Tilsner et al., 2003) to such effect from conventional N fertilization. Greenhouse gas fluxes from landfills are several times higher than from organic-amended agricultural soils (Borjesson and Svensson, 1997; Rinne et al., 2005); therefore, landfilling of wastes, such as biosolids, is discouraged in favor of land application (Wang et al., 2008).

Biosolids are often utilized as amendments for mined soils because they increase soil organic carbon, cation exchange capacity, nutrient levels, and promote ecosystem recovery (Ussiri and Lal, 2005). Application of biosolids to mined soils is the most economic and practical

option of improving soil quality while providing a source of nutrients to the vegetation.

Application of higher than agronomic biosolids rates to mined land reclamation sites is permitted by the Part 503 rule of 40 CFR (USEPA, 1993) and is widely practiced under the assumption that the reclamation benefits from such practice would be greater than possible negative environmental effects (Haering et al., 2000).

Deep row incorporation (DRI) technology is a biosolids land application method, which provides a single application of nutrients sufficient for a short rotation plantation of bioenergy crops, such as hybrid poplar, and has been especially adapted for reclaiming surface mined land (Taylor et al., 1978; Kays et al., 1997; Felix et al., 2008; Felton et al., 2008). Deep row incorporation in mined land involves placement of biosolids in trenches that are immediately covered with overburden, which eliminates odor problems and maintains biosolids in an anaerobic environment. The low oxygen diffusion rate into the entrenched biosolids is expected to reduce mineralization and nitrification rates, allowing the practice to slowly transform nitrogen into plant-available forms and reducing leaching losses of nitrate (Kays et al., 1997). Thus, DRI offers a potentially environmentally beneficial approach for utilizing high rates of biosolids that can be potentially implemented to restore the productivity of surface mined soils.

When biosolids are deep row incorporated, anoxic conditions within the biosolids seam may result in generation of CH<sub>4</sub>, as occurs in landfills (Borjesson et al., 1998; Lohila et al., 2007; Zhang et al., 2009); however, the cover soil and biosolids can develop a population of methanotrophic bacteria that have been shown to mitigate the CH<sub>4</sub> emissions in landfills (Borjesson et al., 1998; Mandernack et al., 2000; Chanton et al., 2009; Scheutz et al., 2009; Zhang et al., 2009). Methanotrophic bacteria can also generate N<sub>2</sub>O via nitrification (Mandernack et al., 2000) and supply simple carbon compounds for denitrifying bacteria growth,

therefore contributing to denitrification (Knowles, 2001; Modin et al., 2007). Application of high rates of organic matter can lead to elevated N<sub>2</sub>O emissions which are able to offset the C sequestered in soil in terms of radiative forcing (Li et al., 2005).

While the DRI biosolids technology has been shown to be beneficial for hybrid poplar growth (Chapter 6) and biomass production (Felix et al., 2008), greenhouse gas dynamics and effects of the DRI biosolids GHG emissions on climate radiative forcing are not clear. It's also unclear how GHG are produced in the biosolids seams with depth and how it affects GHG emissions. Nitrous oxide is produced as a by-product of nitrification and as an intermediate product of denitrification (Knowles, 1982; Wrage et al., 2001; Mathieu et al., 2006), which are likely to simultaneously occur in different parts of the DRI biosolids trench (Sikora et al., 1979). The objectives of our study were: (i) to determine the effects of the DRI biosolids and conventional N fertilization on N<sub>2</sub>O emissions; (ii) to quantify the radiative forcing effects of N<sub>2</sub>O emission from the DRI biosolids and conventional N fertilization and to compare them with such effects of CH<sub>4</sub> and CO<sub>2</sub> emission; (iii) to determine the influence of location in the biosolids seam on N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> emissions.

## **MATERIALS and METHODS**

### **Site Description**

The study was conducted on a mineral sands (ilmenite and zircon) mine reclamation site in Dinwiddie County in Virginia, located 50 km south of Richmond. Slagle (Fine-loamy, siliceous, subactive, thermic, Aquic Hapludults), Myatt (Fine-loamy, siliceous, active, thermic, Typic Endoaquults) and Roanoke (Fine, mixed, semiactive, thermic, Typic Endoaquults) series

originally covered the land prior to mining operations in this area. Post mining soil conditioning resulted from dewatering and sedimentation of sand and clay, physically separated during the mining process (Meredith, 2007). The resulting strongly stratified soil had two distinct particle size fractions: a coarse-textured material (sand) consisting of 96.1% 50 to 2000 $\mu\text{m}$  (sand), 2.0% 2 to 50 $\mu\text{m}$  (silt), and 1.9% <2  $\mu\text{m}$  (clay) and a finer-textured material (sandy clay loam) consisting of 50 to 2000 $\mu\text{m}$  (sand), 8.6% 2 to 50 $\mu\text{m}$  (silt), and 30.2% <2  $\mu\text{m}$  (clay) (Gee and Or, 2002). The soil at the site was mostly represented by the sand fraction which was overlaid by the 0.1-0.5 m layer of the sandy clay loam fraction. The sandy clay loam fraction was also present in fragmentary thin layers in the sand seam. The seasonal water table on the site fluctuated between 1.5 and 4 meters from the soil surface (Orndorff, personal communication).

### **Field Experimental Design**

We compared the following treatments one DRI biosolids rate for each of anaerobically digested (AD) and lime stabilized (LS) biosolids, and two conventional N, P and K fertilizer rates. The four treatments were each replicated 2 times. Each treatment plot was 6 m wide x 15 m long and contained two rows for application of biosolids (trenches) or conventional fertilizer with a row spacing (center-to-center) of 3 m; thus, the area of each of the 8 plots is 90 m<sup>2</sup>. The rows (trenches) were also used to plant hybrid poplar.

Anaerobically digested (AD) and lime stabilized (LS) biosolids were placed in trenches excavated by backhoe the volumetric rate of 90 cm wide $\times$ 75 cm deep, which was equivalent to 2250 m<sup>3</sup> ha<sup>-1</sup>. The biosolids rates were the masses that fit in trenches. We calculated the rates of the biosolids as 426 Mg AD ha<sup>-1</sup> (AD 90 cm) and 656 dry Mg LS ha<sup>-1</sup> (LS 90 cm) after measuring the bulk densities of the biosolids types. The LS biosolids were obtained from Blue Plains

Wastewater Treatment Plant, Washington, DC and were processed by lime stabilization ([http://www.epa.gov/owm/septic/pubs/alkaline\\_stabilization.pdf](http://www.epa.gov/owm/septic/pubs/alkaline_stabilization.pdf)). The AD biosolids were obtained from Alexandria Sanitation Authority, Alexandria, VA and were processed by anaerobic digestion (<http://epa.gov/OWM/mtb/multi-stage.pdf>). Chemical characteristics of AD and LS biosolids are presented in Table 1. The site was established in June and July 2006, when the biosolids were entrenched and covered with fill from the trenches, and the entire area was graded to provide a soil cover of approximately 30 cm over the biosolids trenches.

The conventional fertilizer treatments included fertilizer N surface applied and tilled into the 90 cm wide rows at 0 (Control) and 504 kg N ha<sup>-1</sup> yr<sup>-1</sup>. The fertilizer treatments also received basal applications of 56 kg ha<sup>-1</sup>yr<sup>-1</sup> of triple superphosphate (TSP) and 56 kg ha<sup>-1</sup> yr<sup>-1</sup> of muriate of potash based on soil test recommendations (Donohue and Heckendorn, 1994). Fertilizer N was applied annually in three applications in March, April and May 2007 in the form of ammonium nitrate, and two applications in April and May 2008 in the form of urea. Muriate of potash and TSP were applied annually with the first fertilizer N application. The fertilizer treatments were designed in order to provide the incremental levels of N for hybrid poplar and to compare the effects of conventional fertilization and the DRI on tree growth and greenhouse gas emission.

Hybrid poplar (*Populus deltoides*×*nigra* ‘OP367’) stem cuttings were planted over the center of each biosolids trench and fertilizer row at a spacing of 3 m between plants for a total of 10 trees per plot (3×3 m, 1077 trees ha<sup>-1</sup>) on March 5-6, 2007. The cuttings were purchased from Broadacres Nursery, Inc. (18335 Butteville Road N.E., Hubbard, OR 97032) and shipped refrigerated via U.S. Postal Service to Blacksburg, VA in late February. The 30 cm long cuttings were placed about 20-25 cm into the soil and protected with 30-cm tall, 5-cm diameter staked



plastic tree shelters. The herbicide Roundup™ (2-(phosphonomethylamino) acetic acid) was also sprayed around the trees once each summer in 2007 and 2008 to reduce weed competition with the poplars.

Irrigation was provided during the months of May to September 2007 and June to July 2008 via overhead sprinklers to prevent poplars from succumbing to drought stress. Daily rainfall and temperature were obtained from the U.S. Department of Commerce National Climatic Data Center database ([www.ncdc.noaa.gov](http://www.ncdc.noaa.gov)) according to the closest weather station, located in Sussex County, Stony Creek, VA at 36°58'N / 77°24'W and 32.0m (105') above s/l. Daily mean temperature, precipitation and irrigation data are presented in Figure 5-1.

### **Analysis of Gas Emissions from Field**

We measured N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> emissions in the field using a static chamber technique described by Hutchinson and Mosier (1981). Seven aluminum chambers (volume 1400 cm<sup>3</sup>, cover area 177 cm<sup>2</sup>) were permanently installed in two out of four replicate plots at each of the AD 90 cm, LS 90 cm, 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> and 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatments. Each plot equipped with chambers had five chambers located above the biosolids trenches in AD 90 cm and LS 90 cm, or along the rows of trees in the fertilizer treatments, and two chambers were placed between the rows, in order to account for variability within the plots. At the time of sampling, chambers were closed for 30 min with air tight plastic caps with rubber septa fitted to them, and gas samples were collected with a 10 ml air-tight syringe (Hamilton Co., Reno, NV) immediately after capping (T=0) and after 30 min (T=30) and injected into 4 ml BD Vacutainers (Franklin Lake, NJ) and stored for up to 3 days before analysis on gas chromatography. Sampling was carried out between 9:00 and 12:00 h.

Concentrations of N<sub>2</sub>O and CH<sub>4</sub> were measured using GC-14A gas chromatograph (Shimadzu, Kyoto, Japan) with Alltech Hayesep Q column (1m length, 1/8" diameter, pore size 80/100) operated at 60°C with <sup>63</sup>Ni electron capture detector (ECD) and P5 carrier gas (5% methane/argon) for N<sub>2</sub>O determination, and with flame ionization detector (FID) and He carrier gas for CH<sub>4</sub> determination. Concentrations of CO<sub>2</sub> were measured using Hewlett Packard 5890 gas chromatograph equipped with Alltech Hayesep Q column (1m length, 1/8" diameter, pore size 80/100) operated at 60°C using thermal conductivity detector (TCD) and He carrier gas.

### **Measurements of Gas Emissions from Intact Biosolids Cores**

To understand the dynamics of the N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> production in aged DRI biosolids, we carried out an incubation experiment using the biosolids core samples collected on 27 October 2008, two years after the biosolids entrenchment, as described in Chapter 4. Core incubation was conducted according to the standard procedure of Prieme and Christensen (2001) with modifications. Six intact cores from each sampled seam were obtained by hammering 20 cm long PVC tubes with 4.2 cm inner diameter halfway (10 cm deep) into the excavated DRI biosolids at the edge of the seam (0-5 cm from the side of the trench) and in the seam center (45 cm from the side of the trench) at 0-25 cm, 25-50 cm and 50-75 cm depths and carefully digging the tubes up. Sampling was performed in one seam of each DRI biosolids treatment, resulting in 24 cores for each AD 90 cm and LS 90 cm treatment. Additional cores were collected from each depth for bulk density, moisture content and chemical analyses. Soil cores were collected from the upper 20 cm of the 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment to serve as the control. Fresh AD and LS biosolids cores were obtained at this time from Alexandria Sewer Authority and Blue Plains Wastewater Treatment plants. All cores were stored at 4°C prior to incubation. The cores were

equilibrated at room temperature 21°C for 24 hours, sealed (headspace volume 140 cm<sup>3</sup>, area 14 cm<sup>3</sup>), and gas samples were collected by syringe through a rubber septum at T=0, T=30 min, T=1 h, T=2h. The samples were stored in the vacutainers for up to 3 days before analysis by gas chromatography.

### **Chemical Characterization**

Biosolids used in the study were analyzed for chemical and physical characteristics. Bulk density was determined by weighing the cores and moisture content was determined by comparison of the fresh and dried (65°C for 48 h) weights of the samples. The pH was measured in suspension of 1:2.5 (g/vol) with an Orion PerpHecT logR Benchtop meter (Thermo Scientific, Waltham, MA). Nitrate (NO<sub>3</sub>-N) and NH<sub>4</sub>-N were determined colorimetrically in the 2M KCl extraction and TKN was determined colorimetrically in the Kjeldahl digests using the Lachat 8000 (Lachat Instruments, Loveland, CO). Total organic C was determined by dry combustion on VarioMax CNS analyzer (Elementar, Mt. Laurel, NJ). The biosolids properties are presented in Table 5-1.

### **Statistical Analysis**

The fluxes of N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> were expressed in mg N<sub>2</sub>O/CH<sub>4</sub>/CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup> and standard errors were calculated for every treatment and time, as well as treatment and depth (for the core incubation experiment) combination. Emissions of N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> were tested for treatment and time effects in proc MIXED procedure (SAS Institute Inc., 2008). The spatial power covariance structure was selected for the time series analysis to meet the convergence criteria of the model. The GHG emissions data were log transformed to meet the normality assumption of

statistical analysis. The tests of time and treatment effects were conducted to determine the validity of the time and treatment effects on GHG emissions. Data were also analyzed by differences of least squares means test as a part of the MIXED model analysis (SAS Institute Inc., 2008) (full results output not shown in this chapter but included in Appendix due to its size) to determine significant treatment effects at each sampling time. To describe the dynamics of the N<sub>2</sub>O emissions over time and to quantify the total emissions over the study period, normalized data were fitted (separately for each biosolids treatment and year) to a modified sine emission dynamics model by nonlinear regression using proc NLIN (SAS Institute Inc., 2008) (Gauss-Newton method):  $C_t = a + b \times \sin(k \times (t - c))$ , where  $C_t$  is ln N<sub>2</sub>O, mg m<sup>-2</sup> h<sup>-1</sup>,  $t$  is time, day, and a, b, c and k are fitting parameters. The significance and fit of the estimated ln N<sub>2</sub>O was assessed by the F value of the nonlinear regression and the nonlinear coefficient of determination (*pseudo-r*<sup>2</sup>). This model was selected since regression coefficient (*pseudo-r*<sup>2</sup>) was the highest compared to all other tested models (power, polynomial). A Tukey multiple comparisons procedure in proc GLM (SAS Institute Inc., 2008) was used to distinguish differences in the estimated N<sub>2</sub>O and CO<sub>2</sub>-equivalent emissions.

The influence of the trench depth on released GHG from each of the biosolids types was analyzed using a split plot design with treatment as a main plot factor and depth as a subplot factor in proc MIXED procedure (SAS Institute Inc., 2008). Differences of least squares means procedure was used to determine significant treatment effects at each depth. Normalized GHG fluxes from the biosolids cores were analyzed by stepwise multiple regression using proc REG procedure (SAS Institute Inc., 2008) to determine to what extent biosolids physical and chemical parameters could explain the variation in N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> release. The following parameters

were included in the analysis: pH, moisture content (%), bulk density  $\rho_b$  ( $\text{kg m}^{-3}$ ), organic C (%),  $\text{CO}_3^{2-}$ -C (%),  $\text{NH}_4\text{-N}$  ( $\text{mg kg}^{-1}$ ),  $\text{NO}_3\text{-N}$  ( $\text{mg kg}^{-1}$ ), organic-N ( $\text{mg kg}^{-1}$ ) and TKN ( $\text{mg kg}^{-1}$ ).

## **RESULTS and DISCUSSION**

### **Seasonal Dynamics of $\text{N}_2\text{O}$ Emissions**

The mixed model showed significant ( $P < 0.0001$ ) treatment by time interaction for  $\text{N}_2\text{O}$  emissions during the period of October 2006 to April 2009 (Table 5-2). Treatment effects for  $\text{N}_2\text{O}$  emissions were detected on every sampling date except March 2, 2007 (Table 5-3, Figure 5-2). Despite significant slice by treatment effect for the control treatment (Table 5-2), its absolute values of  $\text{N}_2\text{O}$  emissions never exceeded  $1.1 \text{ mg N}_2\text{O m}^{-2} \text{ h}^{-1}$ . Nitrous oxide fluxes from the fertilizer treatment were significantly higher than the control ( $P < 0.05$ ) during April and June 2007; May, June and July 2008; and April 2009, reaching their highest peaks of 1.2 to  $2.3 \text{ mg N}_2\text{O m}^{-2} \text{ h}^{-1}$ . The biosolids treatments were significantly higher than the control at all times except March 2, 2007 for AD 90 cm and LS 90 cm, and March 5, 2007 for LS 90 cm treatment. Nitrous oxide fluxes from LS 90 cm were not significantly different from the conventional fertilizer during their peaks in spring 2008 and spring 2009. Nitrous oxide emissions from the AD 90 cm were higher than those from LS 90 cm at all times except October 2006 and January to March 2007, when no significant differences between the biosolids treatments were observed. The biosolids treatments reached their peaks in the summer periods of 2007 and 2008, resulting in  $\text{N}_2\text{O}$  emissions on average of 28.0 to  $34.8 \text{ mg N}_2\text{O m}^{-2} \text{ h}^{-1}$  and 2.8 to  $4.0 \text{ mg N}_2\text{O m}^{-2} \text{ h}^{-1}$  for AD 90 cm and LS 90 cm, respectively.

Emissions of  $\text{N}_2\text{O}$  from the DRI biosolids were very high compared to the unfertilized control and the conventional fertilizer treatments. The  $\text{N}_2\text{O}$  fluxes from the biosolids and the fertilizer treatments increased during the warm summer months and decreased during the cold winter months (Figure 2). This agrees with previous measurements of  $\text{N}_2\text{O}$  emissions from fertilizer and biosolids- or manure-amended soils (Christensen, 1983; Jones et al., 2005; Parnaudeau et al., 2009). Significantly higher amounts of  $\text{N}_2\text{O}$  emitted from the biosolids than from the conventional fertilizer treatments were consistent with the previous studies comparing the  $\text{N}_2\text{O}$  emission effects of the fertilizer and organic amendments (Christensen, 1983; Artiola and Pepper, 1992; Barton and Schipper, 2001; Jones et al., 2005). Christensen (1983) obtained a 40-fold increase in emissions from application of cow slurry and  $5\times$  higher emissions after the application of  $\text{NH}_4\text{NO}_3$  to soil. Previous research showed that biosolids utilized as landfill covers produced up to  $56.1 \text{ mg } \text{N}_2\text{O } \text{m}^{-2} \text{ hr}^{-1}$  (Borjesson and Svensson, 1997), which was 1.6 times higher than in our study, possibly due to the 0.3 m of overburden covering the DRI biosolids, which could have reduced  $\text{N}_2\text{O}$  emissions (Zhang et al., 2008). Lime stabilized DRI biosolids emitted lower rates of  $\text{N}_2\text{O}$  than AD 90 cm (Figure 2), likely as a result of reduced microbial activity in the alkaline environment (Smith et al., 1998).

The release of  $\text{N}_2\text{O}$  from the  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  conventional fertilizer treatment resulted in short term post application peaks which were the similar to previously reported 1.1 to  $2.2 \text{ mg } \text{N}_2\text{O } \text{m}^{-2} \text{ hr}^{-1}$  ( $170\text{-}340 \text{ g } \text{N}_2\text{O-N ha}^{-1} \text{ day}^{-1}$ ); however, the  $0 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  control plots in our study released one to two orders of magnitude more  $\text{N}_2\text{O}$  than the  $0.01\text{ to } 0.2 \text{ mg } \text{N}_2\text{O } \text{m}^{-2} \text{ h}^{-1}$  ( $1.4\text{-}28 \text{ g } \text{N}_2\text{O-N ha}^{-1} \text{ day}^{-1}$ ) measured in unfertilized plots in previous studies (Tilsner et al., 2003; Jones et al., 2005; Kavdir et al., 2008). This was an indication that vertical and lateral N transport from the biosolids seams ( $488\text{-}803 \text{ kg N ha}^{-1}$  leached during 2006-2008; Chapter 3)

may have resulted in the elevated N<sub>2</sub>O emissions in the adjacent control and fertilizer treatments. Background levels of N<sub>2</sub>O emission in the 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> plots were similar to those in 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> during the periods other than the N fertilization related spring N<sub>2</sub>O peaks.

### **Cumulative N<sub>2</sub>O Losses**

When ln N<sub>2</sub>O emission values were regressed using the modified sine emission dynamics model, there were significant fits for both biosolids types, with an average pseudo  $R^2$  value of 0.82±0.06 (Table 5-4; Figure 5-2). The total estimated emission of N<sub>2</sub>O for the period of October 2006 to December 2008 was significantly ( $P<0.05$ ) higher for AD 90 cm than LS 90 cm. Conventional fertilizer and the control were not significantly different from each other, and both were significantly lower than the biosolids treatments (Table 5-5). The N<sub>2</sub>O-N lost during the two years as a fraction of the total N applied with the biosolids were 3.5% and 0.6% for the AD 90 cm and LS 90 cm treatments, respectively, and was 1.6× higher than N lost to leaching from the AD 90 cm treatment. Expressed as global warming potentials, N<sub>2</sub>O emissions were equivalent to atmospheric loss of 77% of total organic C applied in the AD 90 cm and 10% of total organic C applied in the LS 90 cm treatment.

N<sub>2</sub>O emission from the biosolids treatments showed significant fits to the modified sine emission dynamics model, while the fits for N<sub>2</sub>O emission from the conventional fertilizer and control treatments were not significant. This may have been due to presence of long-lasting sources of N in the biosolids treatments which resulted in seasonal temperature fluctuation related N<sub>2</sub>O dynamics, while emissions from the fertilizer and control treatments were dependent on N-source limiting processes and only showed the short term peaks of N<sub>2</sub>O emission during the spring and early summer periods. The amplitude of the N<sub>2</sub>O emission in the AD 90 cm

treatment was 1.5 times more in 2008 compared to 2007 (Figure 5-2), which was possibly a result of the DRI biosolids aging causing increased nitrification during summer 2008 (Chapter 3) and production of higher N<sub>2</sub>O amounts via nitrification as well as denitrification pathways (Wrage et al., 2001; Mathieu et al., 2006). During the 2006-2008 study period, the N<sub>2</sub>O flux from the AD 90 cm treatment was 4.6× greater than from LS 90 cm and 14.5× and 16.1× larger than conventional fertilizer and control treatments, respectively. High atmospheric losses of N<sub>2</sub>O-N expressed as global warming potentials (GWP) for the period from October 2006 to December 2008 offset most of the C sequestration gains from the DRI biosolids in terms of climate radiative forcing (Li et al., 2005) for the AD 90 cm treatment, which resulted in 101.5 Mg C ha<sup>-1</sup> equivalent of N<sub>2</sub>O-N lost over a two year period (Table 5-5).

### **Emissions of CH<sub>4</sub> and CO<sub>2</sub>**

Emissions of CH<sub>4</sub> and CO<sub>2</sub>, measured in December 2008 and April 2009 showed significant (P<0.05) treatment by time interactions (Table 5-2). Emissions of CH<sub>4</sub> in conventional fertilizer and control treatments changed with time, resulting in significant (P=0.0634) treatment effects in December 2008 (Table 5-3), when CH<sub>4</sub> emissions in LS 90 cm were significantly higher than the conventional fertilizer and control treatments (Figure 5-3). In April 2009, CH<sub>4</sub> emissions from conventional fertilizer and control treatments were higher than from the AD 90 cm. No significant differences in CH<sub>4</sub> emissions between AD 90 cm and LS occurred. The CO<sub>2</sub> emissions in the control and conventional fertilizer treatments were significantly affected by time and resulted in significant treatment effects in December 2008 (Table 5-2, 5-3), when the CO<sub>2</sub> emissions from LS were higher than the conventional fertilizer and the control treatments. The AD 90 cm and the conventional fertilizer treatments were also



significantly ( $P < 0.05$ ) higher than the control. The  $\text{CO}_2$  emissions were higher from the LS 90 cm than AD 90 cm in December 2008. In April 2009,  $\text{CO}_2$  emissions from LS 90 cm were also higher than the control (Figure 5-3).

It was previously reported that it takes time for methanotrophs to establish in landfill cover soils (Borjesson et al., 1998). Zhang et al. (2009) showed that microbial  $\text{CH}_4$  oxidation activity increased  $4.9\times$  to  $9.8\times$  after soil pre-incubation in the presence of  $\text{CH}_4$  for 3 months. In our study,  $\text{CH}_4$  emissions from the surface of the LS 90 cm treatments were more pronounced, which was possibly due to the lack of methanotrophs in the soil cover and the biosolids seam, as DRI LS biosolids were at earlier mineralization stages than the DRI AD biosolids. High  $\text{CH}_4$  emission from the control and the fertilizer treatments in spring 2009 could have resulted from organic C originating from the lateral leachate from the DRI biosolids present in the saturated soil layers in  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and  $0 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatments, and released as  $\text{CH}_4$  in the anaerobic environment (He et al., 2000). The AD 90 cm treatment  $\text{CH}_4$  flux ( $1.3\text{-}1.8 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ ), however, was not as high as LS 90 cm ( $2.6\text{-}3.9 \text{ mg CH}_4 \text{ m}^{-2} \text{ h}^{-1}$ ) or the spring peak in the control and the fertilizer treatments. This was possibly a result of increased  $\text{CH}_4$  consumption in the upper part of the biosolids trench and the backfill cover by methanotrophic bacteria (Borjesson et al., 1998; Lohila et al., 2007). Methanotrophic bacteria activity was also indicated by the highest rate of  $\text{N}_2\text{O}$  emission from the AD 90 cm (Mandernack et al., 2000; Zhang et al., 2009).

Total  $\text{CO}_2$  emission from the biosolids treatments was 93 to  $563 \text{ mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ , which was similar to previously reported values for sludge amended grasslands during the winter-spring period (Jones et al., 2005). However, the control and conventional fertilizer treatments in our study had 10% to 50% of the respiration in the unamended grassland soils in the study by Jones

et al. (2005), which was possibly due to low organic matter content in the sandy overburden at the site. More pronounced CO<sub>2</sub> respiration in the LS 90 cm treatment was possibly due to CO<sub>2</sub> evolution from the dissolution of CaCO<sub>3</sub> in the lime stabilized biosolids (Smith et al., 1998) by nitrification-borne acidity, or due to increased mineralization of dissolved organic C originating from the biosolids treatment with lime (Curtin et al., 1998). Any of the CO<sub>2</sub> emitted from the biosolids is part of a short-term C cycle; therefore, CO<sub>2</sub> emissions are not considered part of GHG emissions in terms of the radiative forcing (Brown et al., 2008).

The order of contribution to greenhouse gas emissions on GWP in our study as of April 2009 was N<sub>2</sub>O > CO<sub>2</sub> > CH<sub>4</sub> (Table 5-6). Similar trends were valid for both anaerobically digested and lime stabilized DRI biosolids, but it was more pronounced for the AD 90 cm. Our results differed from the existing data on GHG emissions from landfills (Rinne et al., 2005), which showed higher fluxes and GWP of CH<sub>4</sub>. However, our data were similar to the findings by Li et al. (2005) who concluded that cropland management strategies with the emphasis on C sequestration may lead to accumulation of C in soils, but N<sub>2</sub>O emissions will offset significant amounts of the C sequestered.

### **GHG Production in the Biosolids Cores**

The mixed model indicated significant ( $P < 0.0001$ ) treatment effects on N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> fluxes from the DRI biosolids and a significant treatment by depth interaction for CO<sub>2</sub> fluxes after two years of biosolids entrenchment (Table 5-7). The highest fluxes of N<sub>2</sub>O were generated in the centers of the biosolids trenches at the depth of 25-50 cm in AD 90 cm and at 0-25 cm in LS 90 cm (Table 5-8). The N<sub>2</sub>O fluxes from the DRI biosolids were significantly ( $P < 0.05$ ) higher than the original AD and LS biosolids, which were not significantly different from the control

and were essentially negligible. Fresh AD biosolids generated significantly higher fluxes of CH<sub>4</sub>, than AD 90 cm and LS 90 cm treatments. The LS 90 cm treatment was a net sink of CH<sub>4</sub> at 0-50 cm depth. The 0-25 cm depth at the center of LS 90 cm seam had the highest flux of CO<sub>2</sub> compared to the rest of the seam; however, it was not significantly different from the fresh AD biosolids and from the 25-50 cm depth at the edge and the 50-75 cm depth in the center of the AD 90 cm seam. The CO<sub>2</sub> flux from fresh LS biosolids was not significantly different from the control and was significantly lower than fresh AD biosolids, as well as AD 90 cm and LS 90 cm treatments at 0-25 cm depth.

Stepwise multiple regression was performed to identify the factors (pH, moisture content ( $\theta$ ), bulk density ( $\rho_b$ ), organic carbon, carbonates content, NH<sub>4</sub>-N, NO<sub>3</sub>-N, organic-N and TKN) that explained the observed variation of N<sub>2</sub>O, CO<sub>2</sub> and CH<sub>4</sub> fluxes from the biosolids profile. The values of the physical and chemical characteristics within the biosolids seams used in the regression analysis are tabulated in Chapter 4. Moisture content, pH and TKN were the best predictors of N<sub>2</sub>O fluxes according to the following equation:  $\ln N_2O = 12.2(\pm 2.2) \times \theta - 0.5(\pm 0.1) \times pH - 0.00006(\pm 0.00003) \times TKN$  [ $P < 0.05$ ,  $R^2 = 0.55$ ]. Increasing moisture content and decreasing pH and TKN concentrations were associated with significantly higher N<sub>2</sub>O levels. Ammonium-N, TKN and pH were significant predictors of the CH<sub>4</sub> fluxes, which was described by the following equation:  $\ln(CH_4 + 0.25) = -1.6(\pm 0.5) - 0.2(\pm 0.05) \times pH + 0.00004(\pm 0.00001) \times TKN + 0.0003(\pm 0.00005) \times NH_4 - N$  [ $P < 0.05$ ,  $R^2 = 0.59$ ]. Decreasing pH and increasing concentrations of TKN and NH<sub>4</sub>-N were associated with significant increase in CH<sub>4</sub>. Bulk density ( $\rho_b$ ) and pH best predicted CO<sub>2</sub> fluxes according to the equation:  $\ln CO_2 = 12.0(\pm 0.8) - 0.52(\pm 0.01) \times pH - 0.006(\pm 0.002) \times \rho_b$  [ $P < 0.05$ ,  $R^2 = 0.57$ ]. Decreasing pH and bulk density ( $\rho_b$ ) resulted in significantly higher CO<sub>2</sub> levels.

Moisture content, pH, and bulk density were shown to play an important role in the GHG production potential from the disposal of sewage sludge and biosolids recycling (Borjesson and Svensson, 1997; Jones et al., 2005; Kettunen et al., 2006; Zhang et al., 2009). From the results of the biosolids incubation presented above, we conclude that the drier parts of the biosolids trenches had the highest nitrification (Stark and Firestone, 1995), which was the likely primary source of N<sub>2</sub>O production, particularly in the LS 90 cm seams at 0-25 cm depth. Moreover, the average pH in these parts of the seams was 7.65±0.09, which was a near optimum level for nitrification (Kesik et al., 2006; Mathieu et al., 2006). The deeper parts of the LS 90 cm seams produced little N<sub>2</sub>O as their pH (Chapter 4) was much higher than the optimum range for nitrifier activity (Smith et al., 1998; Kesik et al., 2006). Production of N<sub>2</sub>O in the AD 90 cm treatment possibly originated from nitrification in the outer parts of the seam due to lower moisture content of the latter. The AD 90 cm seam center, however, was the highest N<sub>2</sub>O source. Due to the highest moisture content in the centers of the AD 90 cm seams, denitrification possibly was the major source of N<sub>2</sub>O production in the seam centers at 25-50 cm depth, as high NO<sub>3</sub>-N concentrations combined with high moisture create an environment in which high rates of denitrification are expected (Artiola and Pepper, 1992; Prieme and Christensen, 2001; Mathieu et al., 2006). The concentrations of NO<sub>3</sub>-N in the centers of the AD 90 cm seams were as high as 504±190 mg kg<sup>-1</sup> (Chapter 4), which could have increased N<sub>2</sub>O release. It is known that the N<sub>2</sub>O/N<sub>2</sub> ratio increases in abundance of NO<sub>3</sub>-N, which is preferred over N<sub>2</sub>O as an electron acceptor (Knowles, 1982; Ye et al., 1994). Lower amounts of N<sub>2</sub>O released from the edges of the AD 90 cm seams could have been due to pH of 4.65-5.04 (Chapter 4), which is below the optimum level for autotrophic nitrifiers (Kesik et al., 2006; Pietri and Brookes, 2008). Yamulki et al. (1997) also found that the net fluxes of N<sub>2</sub>O decreased as soil pH declined from 7.6 to 3.9.

Lower CH<sub>4</sub> production from the AD 90 cm than the fresh AD biosolids was possibly due to the activity of methanotrophic bacteria, which were previously shown to decrease CH<sub>4</sub> emissions from landfills covered with aged sewage sludge (Borjesson et al., 1998). The LS 90 cm treatments had significant amount of CH<sub>4</sub> uptake at the 0-50 cm depth at the edges of the seams, which was likely due to negligible amounts of CH<sub>4</sub> generated in the alkaline biosolids. This may have resulted in net CH<sub>4</sub> uptake by methanotrophs present in the thin mineralizing outer layer of the DRI LS biosolids. Methanotrophic bacteria were previously shown to engage in nitrification (Mandernack et al., 2000) as well as supply simple carbon compounds for denitrifying bacteria growth and contributing to denitrification (Modin et al., 2007), which result in N<sub>2</sub>O formation. Increased activity of methanotrophs indicated by decreased CH<sub>4</sub> release from the biosolids at the upper parts of DRI AD and LS seams possibly contributed to the high levels of N<sub>2</sub>O release from the DRI biosolids.

High CO<sub>2</sub> release from the surface layer of the LS 90 cm seams possibly resulted from protons generated by nitrification, and their reaction with CaCO<sub>3</sub> present in the biosolids (Smith et al., 1998). Additions of lime could have also contributed to increased mineralization of organic matter and higher CO<sub>2</sub> emissions, as shown by Curtin et al. (1998). Anaerobically digested biosolids gave the highest levels of CO<sub>2</sub> produced at 25 to 50 cm depth, which was indicative of active organic matter mineralization in that portion of the seams.

## CONCLUSIONS

The previous GHG emission studies demonstrated relative importance of greenhouse gases in climate radiative forcing through repeated flux measurements. A limitation in our study

was that CH<sub>4</sub> and CO<sub>2</sub> measurements were done only twice after two years of the biosolids entrenchment, which may have underestimated their effects. However, we were more interested in determining the role of N<sub>2</sub>O, as it was previously shown to offset effects of carbon sequestration in soil (Li et al., 2005). Another limitation was that the biosolids cores used for the incubation were relatively small, which might not be representative of the conditions present in the biosolids trench due to desiccation and shift between the aerobic and anaerobic zones. However, such controlled experiments allow conducting quick comparative analysis of important factors. In addition, the moisture contents measured in the biosolids cores used for the incubation study were not different from the moisture content in the samples collected from the DRI biosolids, therefore we assumed our results were relatively realistic.

Our results suggest that N<sub>2</sub>O is the dominant greenhouse gas emitted from the DRI biosolids examined in this study. Fluxes of N<sub>2</sub>O were influenced by the biosolids pH, and had strong seasonal dynamics, increasing during the summer periods. Conventional N fertilization did not result in significantly higher GWP than the unfertilized control, as its effect may have been masked by the elevated N<sub>2</sub>O emissions due to N groundwater leaching from adjacent DRI biosolids. The contributions of CH<sub>4</sub> and CO<sub>2</sub> to the GWP were small. Our results indicated that deep row incorporation of lime stabilized biosolids may pose a lower risk of high N<sub>2</sub>O emissions leading to elimination of C sequestration benefits from the DRI biosolids in coarse-textured soils compared to anaerobically digested biosolids.

The presented research is a part of the program to evaluate the environmental effects of deep row biosolids incorporation technology. The results will contribute to quantification of C and N mass balance in the short rotation hybrid poplar plantation on the DRI biosolids.

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## TABLES

Table 5-1. Application rates and chemical characteristics of the biosolids used in the study.

Biosolids	Value for characteristic							
	Entrenched mass, dry Mg ha <sup>-1</sup>	Moisture content, %	pH	Organic C, %	Organic N, g kg <sup>-1</sup>	TKN, g kg <sup>-1</sup>	NH <sub>4</sub> -N, g kg <sup>-1</sup>	NO <sub>3</sub> -N, g kg <sup>-1</sup>
AD	426	62.7	8.5	30.7	40.20	53.10	12.90	0.01
LS	656	48.5	12.3	33.0	42.53	44.50	1.97	0.02

Table 5-2. Effects of the biosolids and conventional fertilizer treatments on N<sub>2</sub>O emissions through the course of the experiment (July 2006-December 2008) and on CH<sub>4</sub> and CO<sub>2</sub> emission in December 2008 and April 2009.

Response Variable	p-values			
	Treatment	Time	Trt×Time	
	-----p-values-----			
N <sub>2</sub> O	<.0001	<.0001	<.0001	
CH <sub>4</sub>	0.3094	0.0004	0.0159	
CO <sub>2</sub>	0.0009	0.0106	0.0369	
	Control	504kg N ha <sup>-1</sup> yr <sup>-1</sup>	AD 45 cm	LS 90 cm
	DF			
Treatment×Time	20	19	20	20
Total	514	514	514	514
	-----p-values-----			
N <sub>2</sub> O	<0.0001	<0.0001	<.0001	<.0001
	DF			
Treatment×Time	1	1	1	1
Total	36	36	36	36
	-----p-values-----			
CH <sub>4</sub>	0.0010	0.0008	0.7548	0.3881
CO <sub>2</sub>	0.0010	0.0542	0.9004	0.9712

Analysis conducted in proc MIXED procedure in SAS. All response variables are log transformed.

Table 5-3. Effects of treatments on N<sub>2</sub>O emission at each sampling event during the experiment (July 2006-April 2009) and on CH<sub>4</sub> and CO<sub>2</sub> emission in December 2008 and April 2009.

Time	Trt	p-value		
		N <sub>2</sub> O	CH <sub>4</sub>	CO <sub>2</sub>
6-Oct-06	3	<.0001	-	-
3-Nov-06	3	<.0001	-	-
15-Dec-06	3	<.0001	-	-
5-Jan-07	3	0.0006	-	-
9-Feb-07	3	0.0005	-	-
2-Mar-07	3	0.1699	-	-
5-Mar-07	3	0.004	-	-
23-Mar-07	2	<.0001	-	-
13-Apr-07	3	<.0001	-	-
11-May-07	3	<.0001	-	-
8-Jun-07	3	<.0001	-	-
10-Jul-07	3	<.0001	-	-
9-Aug-07	3	<.0001	-	-
7-Sep-07	3	<.0001	-	-
2-May-08	3	<.0001	-	-
5-Jun-08	3	<.0001	-	-
11-Jul-08	3	<.0001	-	-
26-Sep-08	3	<.0001	-	-
23-Oct-08	3	<.0001	-	-
28-Dec-08	3	<.0001	0.0634	<0.0001
8-Apr-09	3	<.0001	0.1183	0.1283

Analysis conducted in proc MIXED procedure in SAS. All response variables were log transformed.

Table 5-4. Modified sine emission dynamics model for the DRI biosolids treatments  $\ln C_t = a + b \times \sin(k \times (t - c))$  where  $C_t$  is  $\text{N}_2\text{O}$ ,  $\text{mg m}^{-2} \text{h}^{-1}$ ,  $t$  is time, day, and  $a$ ,  $b$ ,  $c$  and  $k$  are fitting parameters. Data was split into two subsets: October 2006 to February 2007, and March 2007 to April 2009.

Model parameters	AD 90 cm		LS 90 cm	
	Oct 06-Feb 07	Mar 07-Apr 09	Oct 06-Feb 07	Mar 07-Apr 09
P-value	<0.0001	0.0722	0.0004	0.0024
<i>pseudo-R</i> <sup>2</sup>	0.879	0.726	0.768	0.964
a	1.88	2.27	0.58	0.49
b	-1.51	-1.58	-0.86	1.00
c	97.53	97.53	66.04	86.34
k	0.02	0.2	0.02	0.01

Table 5-5. Inputs and outputs of N and C, average  $\text{N}_2\text{O}$  emission from the DRI biosolids and conventional fertilizer treatments and change in  $\text{CO}_2$ -equivalent emissions for a 100 year time horizon in the hybrid poplar plantation for the period of October 2006 – December 2008.

Treatment	N applied, $\text{kg ha}^{-1}$	C applied, $\text{Mg ha}^{-1}$	N <sup>a</sup> leached, $\text{kg ha}^{-1}$	Trench Interspaces		$\text{N}_2\text{O}$ , $\text{kg ha}^{-1}$	$\text{N}_2\text{O-N}$ , $\text{kg ha}^{-1}$	C-equiv. <sup>b</sup> , $\text{Mg C ha}^{-1}$
				$\text{N}_2\text{O}$ , $\text{g m}^{-2}$				
AD 90 cm	22600	131	488 a	243.0	74.3	1249.2 a	795.0 a	101.5 a
LS 90 cm	29200	216	803 a	44.8	19.5	270.8 b	172.4 b	22.0 b
504 $\text{kg N ha}^{-1} \text{yr}^{-1}$	1008	-	21 b	8.4	8.6	85.6 c	54.5 c	7.0 c
Control	-	-	4 b	5.5	3.7	77.2 c	49.1 c	6.3 c

<sup>a</sup> N leaching was determined by zero tension lysimeters installed for leachate collection and periodical sampling (Chapter 3).

<sup>b</sup>  $\text{Mg C-equivalents ha}^{-1} = \text{N}_2\text{O, kg ha}^{-1} \times 298 \times 0.001 \text{ Mg kg}^{-1} \times (12 \text{ kg C} / 44 \text{ kg CO}_2)$

Treatments followed by the same letter in each column are not significantly ( $P < 0.05$ ) different.

Table 5-6. Mean emissions of greenhouse gases from the DRI biosolids measured on April 8, 2009 expressed as Global Warming Potentials (GWP) for a 100 year horizon.

	emission, $\text{mg m}^{-2} \text{hr}^{-1}$		$\text{CO}_2$ eq, $\text{mg CO}_2 \text{ m}^{-2} \text{hr}^{-1}$	
	AD 90 cm	LS 90 cm	AD 90 cm	LS 90 cm
$\text{N}_2\text{O}$	14.4	2.4	4291.2	715.2
$\text{CH}_4$	1.3	3.9	32.5	97.5
$\text{CO}_2$	110	480	110	480

Table 5-7. Effects of biosolids treatment and the depth of sampling on N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> emissions.

Response Variable	p-values		
	Treatment	Depth	Treatment×Depth
N <sub>2</sub> O	<0.0001	0.6785	0.4024
CH <sub>4</sub>	<0.0001	0.7808	0.35
CO <sub>2</sub>	<0.0001	<0.0001	<0.0001

Analysis conducted as a split-plot design in proc MIXED procedure in SAS. All response variables are log transformed.

Table 5-8. Average production of N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> from the biosolids treatments at different depths.

Treatment <sup>a</sup>	Core location in seam	Core depth, cm		N <sub>2</sub> O, mg m <sup>-2</sup> hr <sup>-1</sup>		CH <sub>4</sub> , mg m <sup>-2</sup> hr <sup>-1</sup>		CO <sub>2</sub> , mg m <sup>-2</sup> hr <sup>-1</sup>
AD 90 cm	Edge	0-25	A <sup>b</sup>	6.36(±0.71) abcd <sup>c</sup>	B	0.08(±0.04) bcd	A	1908(±331) b
		25-50		47.08(±22.53) bcd		0.54(±0.41) c		3328(±849) ab
		50-75		80.71(±36.66) ab		-0.01(±0.01) cd		1335(±290) bc
	Center	0-25		24.03(±7.75) abcd		0.13(±0.03) bc		1714(±277) b
		25-50		157.26(±46.33) a		0.23(±0.12) bc		2766(±504) b
		50-75		12.87(±2.12) bcd		0.56(±0.50) bc		3104(±519) ab
LS 90 cm	Edge	0-25	B	2.35(±0.54) cd	C	-0.17(±0.07) d	B	1735(±1223) c
		25-50		2.42(±0.35) cd		-0.08(±0.04) d		32(±23) d
		50-75		1.66(±0.35) cde		0.00(±0.04) c		36(±7) d
	Center	0-25		5.48(±1.07) bc		-0.02(±0.04) c		5495(±799) a
		25-50		1.53(±0.36) cd		-0.04(±0.05) c		86(±20) d
		50-75		1.84(±0.43) cde		-0.04(±0.02) c		82(±22) d
AD			C	0.02(±0.01) ef	A	34.35(±1.79) a	A	2815(±11) ab
LS			C	0.04(±0.01) f	C	-0.11(±0.04) de	C	58(±24) d
Control			C	0.04(±0.01) f	C	-0.15(±0.04) e	C	58(±12) d

<sup>a</sup> Deep row applied anaerobically digested (AD 90 cm) or lime stabilized (LS 90 cm) biosolids from the trenches after two years from incorporation, and fresh biosolids of both types (AD, LS) and the unfertilized soil (Control).

<sup>b</sup> Averaged across depths treatment differences of least square means. Treatments followed by the same capital letter in columns are not significantly ( $P<0.05$ ) different.

<sup>c</sup> Treatments followed by the same letter in each column are not significantly ( $P<0.05$ ) different.

## FIGURES

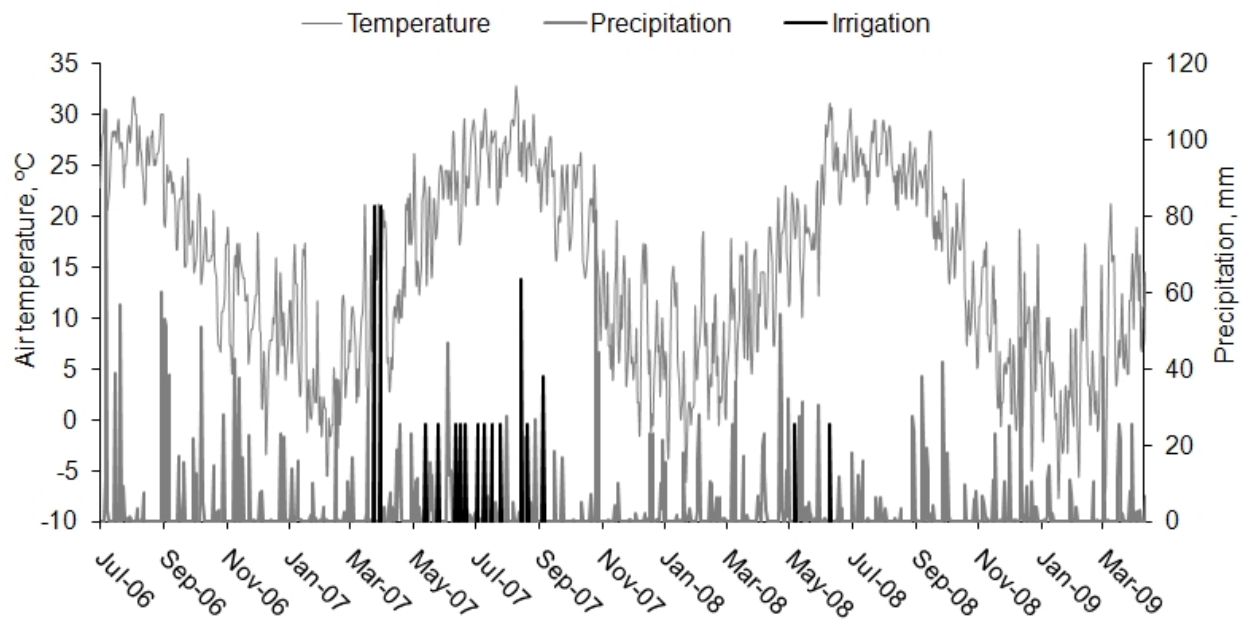


Figure 5-1. Mean temperatures, daily precipitation and irrigation for the research site during the study period between July 2006 and April 2009.



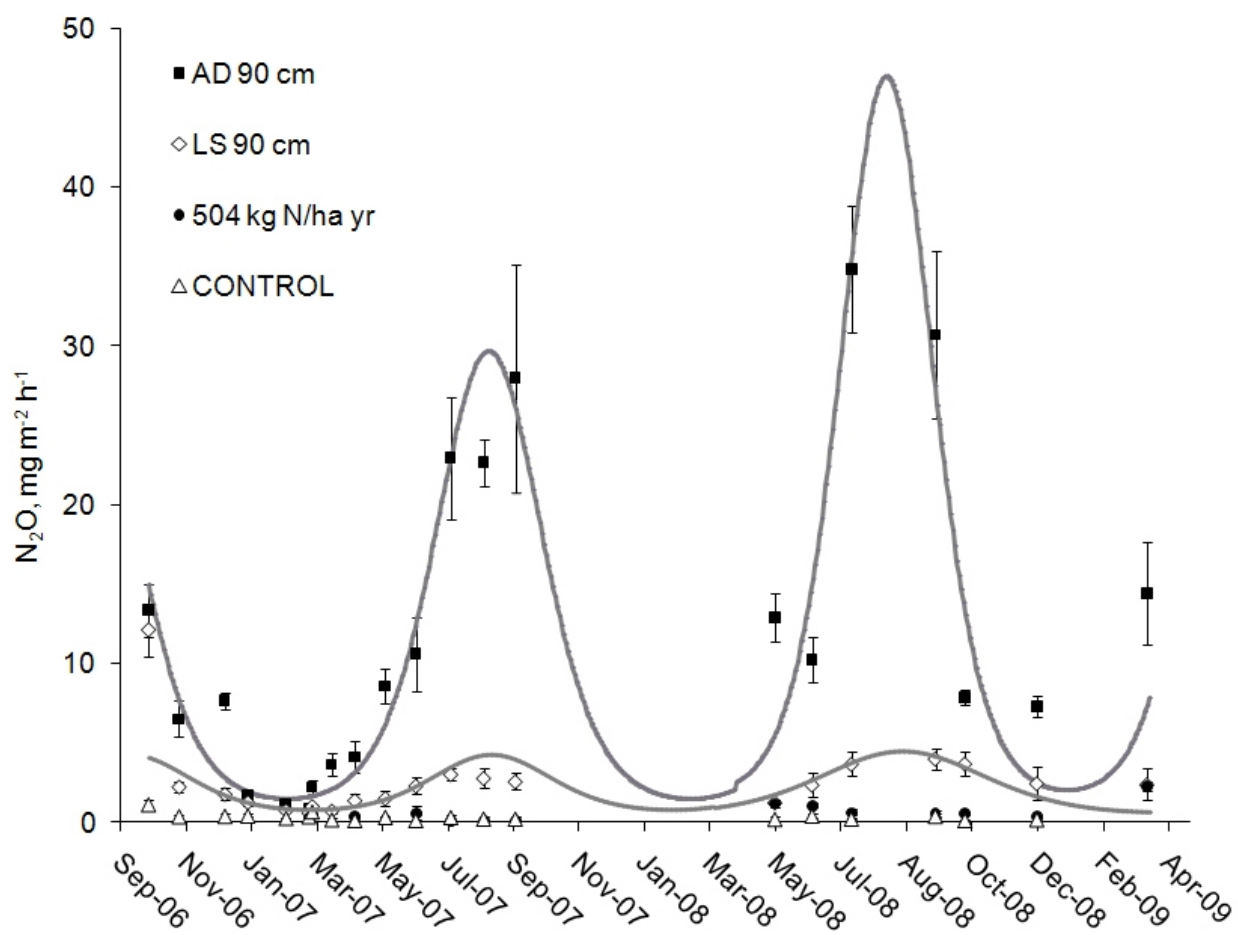


Figure 5-2. Emission of  $N_2O$  from the DRI biosolids and conventional fertilizer treatments in the hybrid poplar plantation for the period of October 2006 – December 2008. Curves represent the modified sine emission dynamics model for the DRI biosolids treatments  $lnC_t = a + b \times \sin(k \times (t - c))$  where  $C_t$  is  $N_2O$ ,  $mg\ m^{-2}\ hr^{-1}$ ,  $t$  is time, day, and  $a$ ,  $b$ ,  $c$  and  $k$  are fitting parameters. Vertical bars represent standard errors.

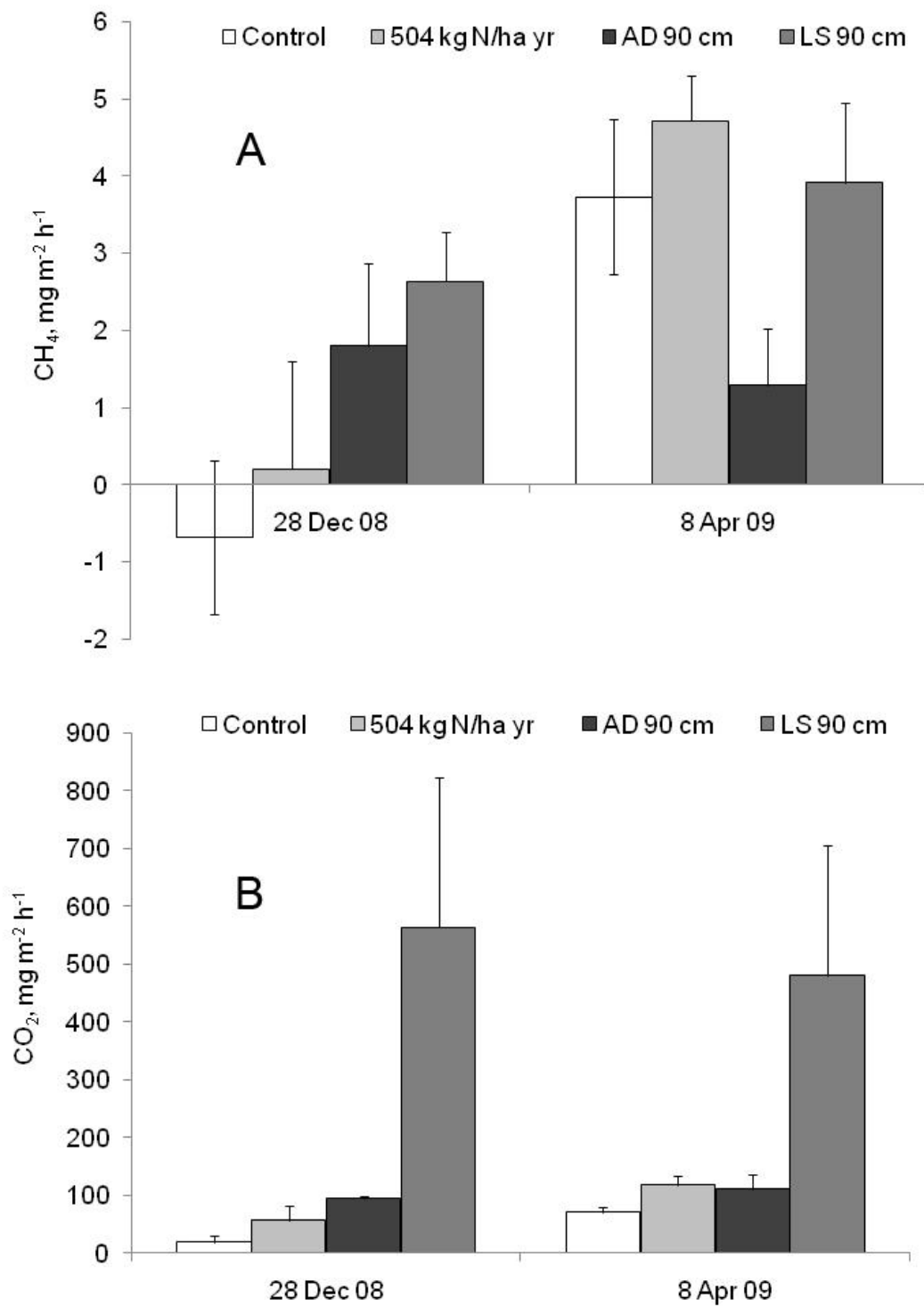


Figure 5-3. Emissions of CH<sub>4</sub> (A) and CO<sub>2</sub> (B) from the DRI biosolids and conventional fertilizer treatments. Vertical bars represent standard errors.

## CHAPTER 6

### **Biomass production, C, N and P Sequestration in Short Rotation Plantation of Hybrid Poplar on Deep Row Applied Biosolids**

#### **ABSTRACT**

Biomass, carbon sequestration, and N and P storage of hybrid poplar (*Populus deltoides* × *nirga* ‘OP367’) were investigated to compare the effects of deep row incorporated (DRI) biosolids and commercial fertilizer on hybrid poplar response. The following eight treatments were established: unfertilized control; 167, 337, 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> as conventional fertilizer; 213 and 426 Mg ha<sup>-1</sup> anaerobically digested and 328 and 656 Mg ha<sup>-1</sup> lime stabilized biosolids applied in trenches. Hybrid poplar was planted at a density of 1077 trees ha<sup>-1</sup>. Tree growth and foliage response was measured after two years of growth. Aboveground biomass production in the biosolids treatments was not different from the control treatment and ranged from 2.1±0.3 to 4.0±0.5 kg tree<sup>-1</sup>. The fertilizer treatments produced significantly less biomass than the control and the biosolids treatments. Hybrid poplars sequestered up to 3.20±0.54 Mg C ha<sup>-1</sup>, 71±12 kg N ha<sup>-1</sup>, and 11.0±1.8 kg P ha<sup>-1</sup>. The planting density capable of the N uptake in order to avoid N leaching was estimated at 3912 to 11363 trees ha<sup>-1</sup>. Our results suggest increased hybrid poplar planting density and decreased application rates of DRI biosolids may decrease the risk of groundwater contamination with N.

## INTRODUCTION

Hybrid poplar (*Populus spp.*) plantations are economically attractive to meet world's increasing demand for forest products (Fox, 2000) due to their high growth rate and biomass production. Poplars are considered one of the most productive hardwood species and, therefore, are commonly grown as short rotation plantations (Karp, 2008), as they can yield substantially more biomass than native forests, particularly when supplemental fertilizer is applied (McLaughlin et al., 1987). Yields of 18.2 dry Mg ha<sup>-1</sup>yr<sup>-1</sup> have been reported for some poplar clones (DeBell et al., 1996), demonstrating poplar's potential as an important carbon sink.

Nitrogen (N) is the nutrient most likely to limit growth, and N fertilization is effective in increasing poplar yields (Hansen et al., 1988). Estimated annual N uptake for poplar trees ranges from 95 to 276 kg ha<sup>-1</sup> year<sup>-1</sup> (Heilman and Stettler, 1986), but poplars are capable of assimilating 224 to 404 kg N ha<sup>-1</sup> year<sup>-1</sup> (National Agroforestry Center, 2000). Phosphorus (P) fertilization also promotes tree growth, but P uptake is several times lower than N. Brown and van den Driessche (2005) found that a single application of 100 kg P ha<sup>-1</sup> resulted in no greater poplar growth than 200 kg P ha<sup>-1</sup> over three years. Fertilization with potassium, zinc and copper may also be necessary to avoid deficiencies induced by N and P additions (Brockley, 2000; van den Driessche, 2000).

Due to high nutrient demands and high maximum growth rate and biomass production (Brown and van den Driessche, 2005), hybrid poplars are very efficient sinks of nutrients at high biosolids application rates. Biosolids cannot be incorporated by tillage into existing poplar plantations due to presence of tree roots (Lteif et al., 2007). Leaving organic amendments on the soil surface increases N loss via ammonia volatilization (Rochette et al., 2001). Pre-plant

biosolids incorporation is preferable to avoid negative effects of biosolids surface application. Deep row incorporation (DRI) technology is a biosolids land application method that provides a single application of nutrients sufficient for a six-year rotation and has been especially adapted for reclaiming surface mined land (Kays et al., 1997; Kays et al., 2000). Deep row incorporation in mined land involves placement of biosolids in trenches that are immediately covered with overburden which eliminates odor problems and maintains biosolids in an anaerobic environment. The low oxygen diffusion rate into the entrenched biosolids is expected to reduce mineralization and nitrification rates, allowing the practice to slowly transform nitrogen into plant-available forms and reducing leaching losses of nitrate (Kays et al., 1997). Thus, DRI offers a potentially environmentally beneficial approach for recycling large amounts of biosolids ( $>383 \text{ Mg ha}^{-1}$ ) that can be potentially utilized to restore productivity of surface mined soils.

Previous studies on DRI biosolids–hybrid poplar plantations demonstrated high tree biomass productivity of poplars within six years of growth but did not explicitly measure poplar uptake of N and P from the biosolids (Felix et al., 2008). Significant amounts of N leaching occurred from the application of biosolids in short rotation poplar plantations using DRI (Felton et al., 2008) and other application techniques (Moffat et al., 2001) when the application rates significantly exceed tree N uptake levels. Deep row incorporated biosolids may also pose potential risks of P leaching and generate significant amounts of highly potent greenhouse gas ( $\text{N}_2\text{O}$  and  $\text{CH}_4$ ) due to anaerobic processes within the trenches (Chapter 5). Therefore, it is important to investigate the effects of DRI on poplar biomass dynamics, carbon sequestration, and N and P uptake in order to assess the potential of hybrid poplar to offset possible environmental effects from the DRI.

The objectives of our study were: (i) to determine the effects of the biosolids on hybrid poplar growth and foliar response; (ii) to determine the influence of poplar growth parameters on the biomass production; (iii) to determine C, N and P sequestration by the poplar plantation in the DRI biosolids; and (iv) to estimate the poplar planting density capable of N uptake to prevent N loss into groundwater from the DRI biosolids.

## **MATERIALS and METHODS**

### **Site Description**

The study was conducted on a mineral sands (ilmenite and zircon) mine reclamation site in Dinwiddie County in Virginia, located 50 km south of Richmond. Slagle (Fine-loamy, siliceous, subactive, thermic, Aquic Hapludults), Myatt (Fine-loamy, siliceous, active, thermic, Typic Endoaquults) and Roanoke (Fine, mixed, semiactive, thermic, Typic Endoaquults) series originally covered the land prior to mining operations in this area. Post mining soil conditioning resulted from dewatering and sedimentation of sand and clay, physically separated during the mining process (Meredith, 2007). The resulting strongly stratified soil had two distinct particle size fractions: a coarse-textured material (sand) consisting of 96.1% 50 to 2000 $\mu\text{m}$  (sand), 2.0% 2 to 50 $\mu\text{m}$  (silt), and 1.9% <2  $\mu\text{m}$  (clay) and a finer-textured material (sandy clay loam) consisting of 50 to 2000 $\mu\text{m}$  (sand), 8.6% 2 to 50 $\mu\text{m}$  (silt), and 30.2% <2  $\mu\text{m}$  (clay) (Gee and Or, 2002). The soil at the site was mostly represented by the sand fraction which was overlaid by the 0.1-0.5 m layer of the sandy clay loam fraction. The sandy clay loam fraction was also present in fragmentary thin layers in the sand seam. Routine soil test analysis results (Donohue and Heckendorn, 1994) of the soil fractions are presented in Table 6-1. The seasonal water table on

the site fluctuated between 1.5 and 4 meters from the soil surface (Orndorff, personal communication).

### **Field Experimental Design**

We established the following 8 treatments: two DRI biosolids rates for each of anaerobically digested (AD) and lime stabilized (LS) biosolids, and four conventional N, P and K fertilizer rates. The eight treatments were each replicated 4 times and arranged in a randomized complete block design. Each treatment plot was 6 m wide x 15 m long and contained two rows for application of biosolids (trenches) or conventional fertilizer with a row spacing (center-to-center) of 3 m; thus, the area of each of the 32 plots is 90 m<sup>2</sup>. The rows (trenches) were also used to plant hybrid poplar.

Anaerobically digested (AD) and lime stabilized (LS) biosolids were placed in trenches excavated by backhoe at two volumetric rates: 45 cm wide×75 cm deep and 90 cm wide×75 cm deep, which was equivalent to 1125 m<sup>3</sup> ha<sup>-1</sup> and 2250 m<sup>3</sup> ha<sup>-1</sup>. The biosolids rates were the masses that fit in trenches. We calculated the rates of the biosolids as 213 dry Mg AD ha<sup>-1</sup>(AD 45 cm), 426 Mg AD ha<sup>-1</sup>(AD 90 cm), 328 dry Mg LS ha<sup>-1</sup> (LS 45 cm) and 656 dry Mg LS ha<sup>-1</sup> (LS 90 cm) after measuring the bulk densities of the biosolids types. The LS biosolids were obtained from Blue Plains Wastewater Treatment Plant, Washington, DC and were processed by lime stabilization ([http://www.epa.gov/owm/septic/pubs/alkaline\\_stabilization.pdf](http://www.epa.gov/owm/septic/pubs/alkaline_stabilization.pdf)). The AD biosolids were obtained from Alexandria Sanitation Authority, Alexandria, VA and were processed by anaerobic digestion (<http://epa.gov/OWM/mtb/multi-stage.pdf>). The site was established in June and July 2006, when the biosolids were entrenched and covered with fill from

the trenches, and the entire area was graded to provide a soil cover of approximately 30 cm over the biosolids trenches.

The conventional fertilizer treatments included fertilizer N surface applied and tilled into the 90 cm wide rows at 0 (Control), 168, 337 and 504 kg N ha<sup>-1</sup> yr<sup>-1</sup>. The fertilizer treatments also received basal applications of 56 kg ha<sup>-1</sup>yr<sup>-1</sup> of triple superphosphate (TSP) and 56 kg ha<sup>-1</sup> yr<sup>-1</sup> of muriate of potash based on soil test recommendations (Donohue and Heckendorn, 1994). Fertilizer N was applied annually in three applications in March, April and May 2007 in the form of ammonium nitrate, and two applications in April and May 2008 in the form of urea. Muriate of potash and TSP were applied annually with the first fertilizer N application. The fertilizer treatments were designed in order to provide the incremental levels of N for hybrid poplar and to compare the effects of conventional fertilization and the DRI on tree growth and N and P leaching.

Hybrid poplar (*Populus deltoides*×*nigra* ‘OP367’) stem cuttings were planted over the center of each biosolids trench and fertilizer row at a spacing of 3 m between plants for a total of 10 trees per plot (3×3 m, 1077 trees ha<sup>-1</sup>) on March 5-6, 2007. The cuttings were purchased from Broadacres Nursery, Inc. (18335 Butteville Road N.E., Hubbard, OR 97032) and shipped refrigerated via U.S. Postal Service to Blacksburg, VA in late February. The 30 cm long cuttings were placed about 20-25 cm into the soil and protected with 30-cm tall, 5-cm diameter staked plastic tree shelters. The herbicide Roundup™ (2-(phosphonomethylamino) acetic acid) was also sprayed around the trees once each summer in 2007 and 2008 to reduce weed competition with the poplars. Irrigation was provided during the months of May to September 2007 and June to July 2008 via overhead sprinklers to prevent poplars from succumbing to drought stress.



### **Biosolids and Soil Sampling and Analysis**

Biosolids used in the study were analyzed for chemical and physical characteristics. Bulk density was determined by weighing the cores and moisture content was determined by comparison of the fresh and dried (65°C for 48 h) weights of the samples. Nitrate (NO<sub>3</sub>-N) and ammonium (NH<sub>4</sub>-N) were determined colorimetrically in the 2M KCl extraction and Total Kjeldahl N (TKN) and Total Kjeldahl P (TKP) were determined in the Kjeldahl digests using flow injection analysis on Lachat 8000 (Lachat Instruments, Loveland, CO). Organic N was determined by the difference between TKN and NH<sub>4</sub>-N. Loading rates of N and P forms were determined for each of the DRI biosolids treatment and presented in Table 2 together with N, P and K annual application rates for the conventional fertilizer and control treatments.

Soil samples were collected from a 15 cm depth in the conventional fertilizer treatments in June 2009 and analyzed for routine soil test analysis of water pH (1:2.5), and Mehlich 1 extractable P, K, Ca, Mg, Zn, Mn and Cu by ICP-AES (Donohue and Heckendorn, 1994).

### **Growth and Foliar Responses**

We measured diameter at breast height (DBH) at 137 cm and basal diameter (BD) at the end of the second growing season in 2008. In April 2009 (before bud break occurred) we measured tree height (HT) and crown radius to calculate the crown volume. We used DBH measurements to estimate individual aboveground leafless biomass (ALB) for each tree from the equations:

$$\text{Equation 1: } ALB, kg = 2.6 \times DBH, cm - 9.64, \text{ where } DBH > 4 \text{ cm}$$

and

$$\text{Equation 2: } ALB, kg = 0.5 \times DBH, cm - 0.35, \text{ where } DBH < 4 \text{ cm,}$$

derived from the biomass relations of the DRI biosolids-hybrid poplar experiment by Felix et al. (2008).

We sampled foliage on August 5, 2008 to measure foliar nutrient response and specific leaf area and weight. We collected a total of fifty fully green leaves from the upper third of the canopy of 5 trees per each plot. Sampling in early August was performed according to recommended sampling protocols for hybrid poplar (Hansen et al., 1988). We used the leaves to determine leaf area size using Licor 3100 leaf area meter. Leaves were oven dried at 65°C for two weeks, weighed and ground to pass a 1 mm sieve in a Wiley mill for further analysis. Total N and P were analyzed using Kjeldahl digestion in sulfuric acid in the presence of  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$  and  $\text{K}_2\text{SO}_4$ . The samples were also digested using concentrated  $\text{HNO}_3$  and 30%  $\text{H}_2\text{O}_2$  and analyzed for total concentrations of K, Ca, Mg, S, Fe, Mn, Al, B, Cu, Mo and Zn via ICP-AEC.

### **Statistical Analysis**

The means and standard errors were calculated for each treatment for the measured tree growth and foliar response parameters. The treatment effects were analyzed with ANOVA and Tukey multiple comparisons test using the GLM procedure (SAS Institute Inc., 2008).

Normalized ALB was regressed on the foliar N via linear regression using proc REG (SAS Institute Inc., 2008). Covariate analysis was used to investigate the effect of the distance from the DRI biosolids trenches (covariate) on the ALB and HT using proc GLM (SAS Institute Inc., 2008). The interaction between the covariate and the factors of ALB and HT was tested for slope differences among factor levels.

## RESULTS and DISCUSSION

### Growth Response

Diameter at breast height (DBH), basal diameter (BD), tree height (HT), crown volume, aboveground leafless biomass (ALB), and roots biomass of the hybrid poplar plantation showed strong treatment effects ( $P < 0.0001$ ) after the second growing season (Table 6-3). All indicators of tree growth in the most of the DRI biosolids treatments were not significantly ( $P = 0.05$ ) different from the unfertilized control after two years of growth. However, AD 45 cm resulted in wider BD than the unfertilized control (Table 6-4). The LS 90 cm treatment also showed lower BD than AD 45 cm, and lower HT than other AD and LS biosolids treatments and the control, which was an indication of possible suppression of poplar root development at the early growth stages by the high volume of the highly alkaline ( $\text{pH} = 12$ ) biosolids beneath the trees. A similar effect was observed in the study by Menon et al. (2005), who reported decreased biomass production of poplar grown with the acidic subsoil ( $\text{pH} = 4.2$ ) layer restricting root development to the topsoil only. Aboveground leafless biomass ALB was not significantly ( $P = 0.05$ ) different among the biosolids treatments and the unfertilized control, and ranged from  $2.1 \pm 0.5$  to  $4.3 \pm 0.5$  kg per tree (Figure 6-1). Crown volume, DBH and root biomass were the same for the biosolids and the control treatments after two years of tree growth.

Incremental conventional fertilization negatively affected tree growth and resulted in lowest values for all tree growth parameters and the ALB of  $1.1 \pm 0.5$  kg per tree for the highest N fertilizer application rate in treatment  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  (Table 6-4). The HT for the  $337 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  fertilizer treatment was significantly lower than the control, the  $168 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatment, and AD 45 cm, AD 90 cm and LS 45 cm biosolids treatments. Both of the higher

fertilizer treatments also produced the least biomass and had the highest stem mortality (indicated by N, total number of trees per treatment) (Table 6-4). The soil test results from the June 2009 sampling regimen, however, did not show any significant differences in pH, soil P, K, Ca, Mg, Zn, Mn or Cu among the fertilizer and the control treatments (Table 6-1). Therefore, we hypothesize that decreased tree growth was a result of some unmeasured effects of conventional fertilization. A possible scenario is a short-lived decrease in soil pH due to application of N fertilizer and ammonia-nitrification-generated acidity (Barak et al., 1997) in the sandy-textured mine backfill. Acidic subsoil with pH=4.2 was shown to impede deciduous trees root growth and cause root density concentrate near the surface, which also resulted in decreased aboveground biomass production in the second year of growth compared to calcareous soil (Menon et al., 2005). Increases in soluble salts content (EC) were shown to contribute to root damage and decreased biomass production in poplar (Mertens et al., 2004). Similar short-term increase in EC from the application of 150 kg N ha<sup>-1</sup> of urea and NH<sub>4</sub><sup>+</sup> release as a result of urea hydrolysis was demonstrated to decrease growth in corn (Ouyang et al., 1998). In our study a possible temporary decrease in pH below 5.0 which is the lowest acceptable pH for hybrid poplar (Stanturf, 2001) or a short-term increase in EC due to NH<sub>4</sub>-N originating from hydrolysis of urea could result in similar effects of root damage and decreased biomass production of hybrid poplar. The highest stem mortality of 27.5% in the 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment also indicated that some negative fertilization-related effects took place.

### **Foliar Response**

We detected significant (P<0.05) treatment effects for the foliar response parameters during the second growing season (Table 6-4). Individual leaf area in the AD 90 cm biosolids

treatment was  $90 \pm 4 \text{ cm}^2$  per leaf, which was significantly higher than the control and the  $168 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  fertilizer treatment (Table 6-4). Specific leaf area and leaf weight (data not shown) were not significantly different among treatments.

The AD 90 cm and  $337 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatments also had the highest foliar concentration of nitrogen. The foliar N content in these treatments was  $33.6\text{-}33.9 \text{ mg g}^{-1}$  on average, which was in the range of reported luxury N uptake levels for hybrid poplar above  $30 \text{ mg g}^{-1}$  (Hansen et al., 1988; Coleman et al., 2006). The LS 90 cm treatment had  $26.1 \pm 1.5 \text{ mg g}^{-1}$  of foliar N, which was significantly ( $P=0.05$ ) lower than AD 45 cm and AD 90 cm biosolids treatments and the  $337 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatment, but still above the N sufficiency level of  $20\text{-}30 \text{ mg g}^{-1}$  (Coleman, 1998). There was no relationship ( $P=0.9706$ ) between foliar N concentration and ALB (Figure 6-2), which indicated that N was sufficient in all treatments, including unfertilized control.

Phosphorus concentrations in the foliage followed the same trend as for N. The LS 90 cm and  $337 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatments had the lowest P levels of  $2.2 \pm 0.3 \text{ mg g}^{-1}$ , which is borderline P deficiency for hybrid poplar foliage (van den Driessche, 2000; Coleman et al., 2006). Decreased P levels for the poplars growing in lime stabilized biosolids may have been due to a high P binding capacity of the Fe-rich alkaline biosolids. This also might have been due to insufficiently developed tree roots, which could not exploit the immobile P resources (van den Driessche, 1999). The AD 90 cm treatment had the highest foliar P level of  $3.4 \pm 0.7 \text{ mg g}^{-1}$ , which was an indicator of better phosphorus availability to hybrid poplar from the anaerobically digested DRI biosolids during the second growing season (Table 6-4).

Most of the other nutrients foliar concentrations remained the same among treatments (Table 6-5), and were within the levels common for *Populus* species (Zalesny and Bauer, 2007b). However, Zn significantly ( $P<0.05$ ) declined in the  $504 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  and the AD and LS

biosolids treatments compared to the control and 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment, reaching its lowest values of 19.2±4.2 µg g<sup>-1</sup> in the LS 90 cm. Foliar Mn was also significantly lower in the 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> and AD 45 cm treatment (Table 6-5). Despite the differences in foliar Zn levels, they were within the sufficiency range for hybrid poplar (Thomas et al., 2007), and the trees did not show any Zn deficiency symptoms. Moreover, we observed the highest biomass production of 4.0±0.5 kg tree<sup>-1</sup> in the LS 45 cm biosolids treatment (Table 6-4), which had 7 times less foliar Zn than the unfertilized control.

Previous studies showed decreased foliar Zn concentrations in the poplar treatments which received lower amounts of Zn with amendments (Di Baccio et al., 2003; Vandecasteele et al., 2003; Sebastiani et al., 2004) or were grown in non Zn-contaminated soils (Mertens et al., 2004). Application of biosolids delivers significant amounts of Zn (Lasley et al., in review-a), which was shown to increase the Zn content in poplar foliage (Sebastiani et al., 2004). The DRI biosolids applied in our study leached the highest rates of Zn from the seams during fall 2006, with organic matter-bound Zn fraction dominating in the leachate (Lasley et al., in review-b). However, Zn leaching significantly decreased (Lasley et al., in review-a), as decreased the leachate pH to as low as 4.5±0.5 due to nitrification-borne acidity (Chapter 3), which was possibly a result of decreased organic C leaching (Curtin et al., 1998; Kemmitt et al., 2006) and stabilization of metal-organic matter-Al, Fe oxide complexes (Lasley et al., in review-b). High fertilizer N application was previously shown to cause short-term increase in soil EC (Ouyang et al., 1998) and acidity (Barak et al., 1997), both of which were demonstrated to be interrelated with impeded root development and biomass growth in poplar (Mertens et al., 2004; Menon et al., 2005). Therefore, we hypothesize that poplar roots were impeded as a result of high N fertilization effects in the 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment. We also hypothesize that the tree roots

avoided the areas affected by low leachate pH in the soil surrounding the AD and LS biosolids seams. That likely resulted in localizing most of the root densities near the surface in the sandy soil with Zn content of 0.8–1.3 mg kg<sup>-1</sup> on average, which was low compared to the natural range of 30-150 mg Zn kg<sup>-1</sup> (Mulligan et al., 1999; Di Baccio et al., 2003), and causing decreased foliar Zn. The control and 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatments had higher foliar Zn content as root growth and development likely did not encounter possible negative effects of DRI biosolids and high N fertilization, and roots could invade deeper soil horizons and uptake Zn from the areas enriched by the DRI biosolids. Moreover, the control 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment demonstrated good biomass growth and lack of N deficiency, which suggested ability of the poplar trees to utilize the nutrients from the adjacent plots.

#### **Effects of the DRI biosolids on Tree Growth in Conventional Fertilizer Treatments**

We conducted ANCOVA to test for possible effects of the adjacent plots with the DRI biosolids on the ALB response and HT in the fertilizer treatments and the control. Analysis of covariance for ALB and HT versus the distance to the closest biosolids seam, showed significant interaction of the distance to the biosolids seam by treatment effect for ALB (P=0.0150) and HT (P=0.0004), which indicated that the assumption of homogeneity of regression coefficients across the categorical variable (treatment) of ANCOVA analysis was violated (Table 6-6). Therefore traditional ANCOVA which assumes the slopes for all the treatments are the same could not be used, and we had to interpret the effect of the biosolids trench on ALB or HT in the fertilizer treatments by referring to the specific distances from the DRI biosolids.

The DRI biosolids significantly (P=0.0163) increased ALB in the 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> fertilizer treatment by 40% at the distance of 3 m, compared to 6 m from the adjacent biosolids

trench (Table 6-7). The 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment showed increased (P=0.0106) productivity at the distance of 12 m compared to 3 m from the seam, which suggested that the biomass increase occurred due to factors other than the biosolids seam. The control and the 337 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatments ALB production was not significantly (P>0.05) affected by the biosolids seam (Table 6-7).

Tree height HT significantly (P=0.0004) increased in the 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment at the distance of 12 m as compared to 3 m from the DRI biosolids (Table 6-8), which was in agreement with ALB production increase, and possibly occurred due to factors not related to the DRI biosolids. No other significant effects (P>0.05) of the adjacent biosolids treatments on HT were found.

Overall, we didn't observe strong effects of the adjacent DRI biosolids plots on conventional fertilizer treatments. The effects were limited to increase in ALB production in the 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment at 3 m from the biosolids seam. Nevertheless, the 504 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment had the lowest tree growth characteristics among all treatments. However, the leaching data showed significant NO<sub>3</sub>-N migration at concentrations up to 251 mg l<sup>-1</sup> by lateral flow in the soil surrounding the biosolids seams (Chapter 3). High NO<sub>3</sub>-N lateral leaching, high biomass growth and lack of N deficiency in the control 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment were indicative of the poplar ability to uptake nutrients from the adjacent plots. Therefore, we hypothesize that effects of fertilization by the mobile nutrients from the biosolids treatments took place despite the lack of distance from the biosolids seams effects on the ALB and HT.



### **Biomass Production, C, N and P Storage**

Biomass production by hybrid poplar was estimated from ALB (as  $\text{kg tree}^{-1}$ ) and roots biomass (as  $\text{kg tree}^{-1}$ ) for each experimental plot, based on the tree planting density of 1077 stems  $\text{ha}^{-1}$ . Carbon content in biomass was taken from the average published values (Zabek and Prescott, 2006; Fang et al., 2007). Nitrogen and P concentrations in the biomass were obtained from the published values (Heilman and Stettler, 1986; Pregitzer et al., 2000) and confirmed by our measurements (Table 6-9).

The AD 90 cm, LS 45 cm, control, and 168  $\text{kg N ha}^{-1} \text{ yr}^{-1}$  treatments produced the most aboveground biomass, which ranged from  $3.0 \pm 0.5$  to  $4.63 \pm 0.51 \text{ Mg ha}^{-1}$ , and was significantly ( $P < 0.05$ ) higher than 337  $\text{kg N ha}^{-1} \text{ yr}^{-1}$  and 504  $\text{kg N ha}^{-1} \text{ yr}^{-1}$  treatments (Table 6-10). The LS 90 cm treatment total biomass production was not significantly ( $P > 0.05$ ) different from other DRI biosolids or conventional treatments. Despite the lack of differences in biomass production among the biosolids and the control treatments, we expect the biosolids treatments to exceed the unfertilized control in biomass production during subsequent years, as the foliar N concentrations indicated luxury N uptake by the trees in the biosolids treatments compared to the control. The DRI biosolids–hybrid poplar plantation study conducted by Felix et al. (2008) reported the mean values of tree aboveground biomass of  $0.3 \pm 0.2 \text{ kg tree}^{-1}$  ( $0.3 \text{ Mg ha}^{-1}$ ) on the second year of growth, and only the three to four year old trees achieved growth of 3.0 to 4.6  $\text{kg tree}^{-1}$  (3.2 to 5.0  $\text{Mg ha}^{-1}$ ), which was similar to our study after two years of growth. Zalesny et al. (2007) obtained aboveground biomass of 0.51 to 2.50  $\text{Mg ha}^{-1}$  after two years of hybrid poplar growth under landfill leachate irrigation at  $1.2 \times 2.4 \text{ m}$  (3472 trees  $\text{ha}^{-1}$ ) spacing. Another study conducted at  $2 \times 2 \text{ m}$  (2500 trees  $\text{ha}^{-1}$ ) showed poplar biomass after two years of growth between 2.1 and 13.2  $\text{Mg ha}^{-1}$ , depending on the poplar clone (Armstrong et al., 1999).

The amount of C sequestered by the trees reached its highest values of up to  $3.20 \pm 0.54$  Mg ha<sup>-1</sup> in the AD 90 cm and LS 45 cm treatments and was not significantly different from the control or the 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment, which stayed in the range of  $2.07 \pm 0.36$  to  $2.11 \pm 0.31$  Mg ha<sup>-1</sup>. Nitrogen and P storage in the tree biomass followed similar patterns, attaining maxima of  $71 \pm 12$  kg N ha<sup>-1</sup>, and  $11.0 \pm 1.8$  kg P ha<sup>-1</sup>, respectively (Table 6-10). These values showed the N and P storage and C sequestration by the hybrid poplar at the tree density of 1077 trees ha<sup>-1</sup> grown on the DRI biosolids in the Coastal Plain sand mine reclamation site with shallow groundwater, after two growing seasons. Our data indicated that N sequestration by the trees was 3-10 times less than N leaching into groundwater however, P sequestration exceeded P groundwater leaching (Table 6-11), estimated for the period of July 2006-October 2008 based on the results of Chapter 3. The results also demonstrated hybrid poplar growth on post-mining coarse-textured soils with low organic matter and low cation exchange capacity can have reduced biomass production and N uptake when excessively fertilized with ammonium nitrate and urea (Table 6-10).

We also estimated the total C, N and P sequestration by the DRI biosolids-hybrid poplar plantation at the density of 1077 trees ha<sup>-1</sup>, based on the maximum aboveground biomass, achieved after six years of growth in the study by Felix et al. (2008) using the average poplar C, N and P concentrations (Table 6-9). Our calculations (Table 6-12) showed that within six years the trees could sequester 339 kg N ha<sup>-1</sup>, which was comparable with the leaching rates from the DRI biosolids in the sandy mine reclamation site after only two years of entrenchment (Table 6-11). Four year old poplars at 1.2×1.2 m spacing (6900 trees ha<sup>-1</sup>) resulted in the 95 to 420 kg N ha<sup>-1</sup> sequestered in the aboveground biomass (Heilman and Stettler, 1986), which was equivalent to 131 to 580 kg N ha<sup>-1</sup> in total biomass. Moffat et al. (2001) showed that the application of the

sewage sludge effluent in excess of the poplar uptake levels resulted in high concentrations of N in leachate. The trees, however, were capable of sequestering the amount of P, which was 33 times higher than the P that could possibly be lost into groundwater after six years, assuming the maximum P leaching rate were not different from the values obtained in our study. Our calculations indicated that it would take 33 consecutive six year poplar plantations at the given tree density or 198 years to sequester all the N applied with the lowest AD 45 cm DRI biosolids treatment ( $11.3 \text{ Mg N ha}^{-1}$ ), if there were no N losses other than removal with the harvest from the system.; therefore, excessive N leaching would be inevitable due to mineralization of N applied in excess to poplar N needs.

### **Tree Spacing and N Uptake**

It was important to provide a possible solution for the DRI biosolids–hybrid poplar plantation technology, which would be beneficial and environmentally safe. We estimated the possible tree densities that could provide N uptake levels in order to minimize N leaching from the DRI biosolids. We used a linear approach for the tree growth–tree density relationship, as previous research has shown that the tree densities of interest, which result in the spacing of  $1 \times 1$  to  $3 \times 3$  m had a linear increase in annual biomass production in the first two years of growth (Armstrong et al., 1999; Fang et al., 2007). Trees planted at the spacing of  $1.22 \times 1.22$  to  $0.3 \times 0.3$  m had a logarithmic aboveground biomass increase (Figure 6-3); therefore, such densities, particularly at their upper end, should not be expected to increase the biomass production and N uptake in the linear fashion. We used the mean N leaching rates for the period from July 2006 to October 2008 and the total tree N uptake of  $71 \pm 12 \text{ kg ha}^{-1}$  at the tree density of  $1077 \text{ trees ha}^{-1}$ , which corresponds to the spacing of  $3 \times 3$  m to extrapolate the tree density up to  $11500 \text{ trees ha}^{-1}$

(Figure 6-4). Our estimates showed that the tree density range required to uptake the N from the DRI biosolids leachate within the first two years of growth would be 3912 to 11363 trees ha<sup>-1</sup>, which is equivalent to 1.6×1.6 m to 0.95×0.95 m spacing. Although higher tree densities may result in lower timber quality (Felton et al., 2008), it is environmentally beneficial to use higher tree densities to prevent excessive N leaching and groundwater pollution. Given the results of our study, the tree density information can be adapted to similar hybrid poplar production sites at the establishment stage to meet the water quality and biomass productivity goals.

## CONCLUSIONS

The obtained results suggest that the DRI biosolids provide a favorable environment for growth and development of hybrid poplar when compared with the similar rates of conventional fertilizer; however, they present several drawbacks. Such drawbacks include reduced biomass production and nutrient uptake by the trees grown the highest rate of lime stabilized DRI biosolids, possibly as a result of impeded root growth at the initial development stages. Significant loss of N into groundwater due to biosolids N mineralization rate greatly exceeding tree N uptake rate poses a serious water quality issue in the coarse-textured soils. Although EPA permits higher than required biosolids application rates for the purpose of achieving the reclamation goals at mined land sites (Haering et al., 2000), annual N losses to the groundwater comparable with the N uptake levels for the six year rotation are likely to result in significant damage to the local groundwater quality and, therefore, should be avoided by decreasing the biosolids entrenchment rates and increasing tree planting density.

The presented research is a part of the research program to evaluate the environmental effects of deep row biosolids incorporation technology. The results will contribute to quantification of the C, N and P mass balance in the short rotation plantation on the DRI biosolids.

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## TABLES

Table 6-1. Characteristics of sand and sandy clay loam fractions that comprised the reclaimed minesoil and soil properties of the upper 15 cm in the hybrid poplar-conventional fertilization treatments in June 2009.

Mine backfill fractions	pH	P	K	Ca	Mg	Zn	Mn	Cu
		-----mg kg <sup>-1</sup> -----						
sand	6.1	11	15	149	31	0.6	1.2	0.1
sandy clay loam	6.8	63	101	752	152	3.9	9.1	0.5

Treatment	-----mg kg <sup>-1</sup> -----							
Control	6.7±0.4 a	42±3 a	77±20 a	382±31 a	74±8 a	0.8±0.1 a	3.2±0.1 a	0.4±0.0 a
168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	6.5±0.3 a	59±6 a	80±21 a	426±42 a	81±2 a	1.3±0.4 a	4.6±0.6 a	0.4±0.1 a
337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	5.8±0.4 a	56±13 a	85±14 a	309±49 a	64±9 a	0.9±0.2 a	4.0±0.3 a	0.3±0.1 a
504 kg N ha <sup>-1</sup> yr <sup>-1</sup>	6.5±0.4 a	71±11 a	45±12 a	352±44 a	60±10 a	0.8±0.1 a	3.6±0.7 a	0.2±0.0 a

\*Treatments in each column followed by the same letter are not significantly different (P=0.05).

Table 6-2. Annual application rates of N, P and K to the conventional fertilizer treatments, and loading rates for N and P forms in the DRI biosolids treatments in the hybrid poplar plantation.

Treatment	Trench width, cm	Annual fertilization			Biosolids constituents loading rates			
		N	P (TSP)	K (KCl)	N, organic	NH <sub>4</sub> -N	NO <sub>3</sub> -N	P
		-----Kg ha <sup>-1</sup> -----						
Control	-	-	56	56	-	-	-	-
168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	-	168	56	56	-	-	-	-
337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	-	337	56	56	-	-	-	-
504 kg N ha <sup>-1</sup> yr <sup>-1</sup>	-	504	56	56	-	-	-	-
AD 45 cm	45	-	-	-	8,560	2,750	2	5,650
AD 90 cm	90	-	-	-	17,130	5,490	3	11,300
LS 45 cm	45	-	-	-	13,970	646	5	2,850
LS 90 cm	90	-	-	-	27,940	1,290	10	5,690

\*Nitrogen fertilization was conducted in spring 2007 (ammonium nitrate) in three applications in March, April and May, and in spring 2008 (urea) in two applications in March and in May. Triple superphosphate (TSP) and potash (KCl) were applied with the first N application each year.

Table 6-3. Analysis of variance degrees of freedom and P-values for the variables tested using a randomized complete block design.

	DF		p value
	Error	trt	
DBH, cm	271	7	<0.0001
BD, cm	271	7	<0.0001
HT, m	271	7	<0.0001
Crown volume, m <sup>3</sup>	271	7	<0.0001
ALB, kg	271	7	<0.0001
Root biomass, kg	271	7	<0.0001
Individual leaf area, cm <sup>2</sup>	21	7	0.0263
Specific leaf area, cm <sup>2</sup> g <sup>-1</sup>	21	7	0.1114
Leaf weight, g	21	7	0.0482
N, mg/g	21	7	0.0012
P, mg/g	21	7	0.0011

Table 6-4. Diameter at breast height (DBH), basal diameter (BD), tree height (HT), crown volume, aboveground leafless biomass (ALB), roots biomass, individual leaf area, specific leaf area, and foliar N and P concentrations for the hybrid poplar plantation at the second growing season (October 2008).\*

Treatment	N	DBH, cm	BD, cm	HT, m	Crown volume, m <sup>3</sup>	ALB, kg <sup>‡</sup>	Root biomass, kg <sup>†</sup>	Individual leaf area, cm <sup>2</sup>	Specific leaf area, cm <sup>2</sup> g <sup>-1</sup>	N, mg g <sup>-1</sup>	P, mg g <sup>-1</sup>
Control	40	4.3±0.2 ab	7.4±0.3 bc	4.4±0.1 a	4.7±2.0 ab	2.8±0.4 ab	1.1±0.2 ab	68±4 b	139±5 a	27.5±0.7 bc	2.4±0.2 bc
168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	36	4.3±0.2 ab	6.9±0.4 bc	4.1±0.1 b	4.0±1.7 ab	2.8±0.5 ab	1.1±0.2 ab	63±4 b	130±5 a	28.7±3.6 abc	2.2±0.3 c
337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	33	3.8±0.3 bc	6.5±0.4 cd	3.7±0.1 bc	3.6±1.8 bc	2.3±0.4 bc	0.9±0.1 bc	70±5 ab	129±5 a	33.6±4.5 a	2.3±0.2 bc
504 kg N ha <sup>-1</sup> yr <sup>-1</sup>	29	3.0±0.3 c	5.4±0.4 d	3.3±0.1 c	1.9±1.2 c	1.1±0.1 c	0.4±0 c	75±7 ab	122±7 a	29.5±1.4 abc	2.5±0.1 abc
AD 45 cm	37	4.8±0.2 a	8.8±0.4 a	4.5±0.1 a	6.5±2.4 a	3.8±0.5 ab	1.4±0.2 ab	76±7 ab	130±2 a	32.6±1.7 ab	2.9±0.3 ab
AD 90 cm	34	5.1±0.3 a	7.9±0.4 ab	4.5±0.2 a	5.0±2.1 ab	4.3±0.7 ab	1.6±0.3 ab	90±4 a	130±5 a	33.9±2.0 a	3.4±0.7 a
LS 45 cm	38	4.9±0.2 a	8.3±0.4 ab	4.4±0.2 a	5.1±1.9 ab	4.0±0.5 a	1.5±0.2 a	77±4 ab	136±7 a	28.3±1.7 abc	2.4±0.2 abc
LS 90 cm	37	3.9±0.2 abc	7.1±0.4 bc	3.7±0.1 bc	4.0±1.5 ab	2.1±0.3 abc	0.8±0.1 abc	76±6 ab	143±9 a	26.1±1.5 c	2.2±0.2 c

\* Treatment means with standard errors within each column followed by the same letters are not significantly different (P=0.05).

Tukey's Studentized Range (HSD) test performed in proc GLM procedure.

‡ Calculated via allometric functions (Felix et al., 2008)

† Calculated via ALB based on roots/shoots ratio of 0.38 (Heilman and Xie, 1993)

Table 6-5. Hybrid poplar foliar nutrient concentrations for upper canopy foliage sampled in August 2008 at the second year of growth (August 2008).

Treatment	K	Ca	Mg	S	Fe	Mn	Al	B	Cu	Mo	Zn
	-----mg g <sup>-1</sup> -----				-----µg g <sup>-1</sup> -----						
Control	20.4±4.3 a	15.7±4.3 a	5.1±1.3 a	4.6±1.3 a	95.5±25.1 a	329±76 a	31.1±6.8 a	65.9±17.6 a	4.6±2.0 a	0.16±0.15 a	230±56 a
168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	14.6±3.0 a	9.3±1.3 a	3.2±0.5 a	3.7±0.8 a	67.1±11.4 a	216±22 ab	21.4±3.4 a	46.3±10.0 a	3.6±1.0 a	0.01±0 a	183±27 a
337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	17.9±1.2 a	11.8±1.3 a	3.3±0.1 a	3.6±0.2 a	78.1±2.3 a	125±37 ab	22.4±1.5 a	36.6±7.9 a	3.7±0.6 a	0.38±0.23 a	83.4±26 ab
504 kg N ha <sup>-1</sup> yr <sup>-1</sup>	19.4±1.7 a	11.2±1.3 a	3.1±0.2 a	3.4±0.2 a	75.9±6.6 a	83.0±21 b	21.8±3.4 a	23.2±2.4 a	2.5±0.5 a	0.17±0.17 a	44.4±5.5 bc
AD 45 cm	21.2±4.4 a	13.8±3.8 a	4.2±0.9 a	3.7±0.7 a	84.7±16.4 a	98.3±25 b	25.7±5.1 a	22.9±5.6 a	5.0±1.5 a	0.01±0 a	28.4±2.5 bc
AD 90 cm	27.6±4.5 a	22.8±6.4 a	6.7±1.6 a	5.3±1.0 a	111±17.0 a	150±41 ab	42.6±9.0 a	33.7±13.0 a	1.5±0.7 a	0.68±0.40 a	42.1±23.2 bc
LS 45 cm	20.6±1.7 a	14.9±1.4 a	5.0±0.7 a	3.7±0.2 a	96.3±6.4 a	162±10 ab	45.6±3.6 a	18.4±1.8 a	1.3±0.8 a	0.35±0.21 a	34.0±11.5 bc
LS 90 cm	17.4±3.4 a	14.0±1.0 a	5.1±0.3 a	3.0±0.5 a	76.2±4.2 a	114±18 ab	35.9±3.6 a	20.6±3.6 a	0.3±0.3 a	0.64±0.41 a	19.2±4.2 c

Table 6-6. Analysis of covariance for the interaction between aboveground leafless biomass (ALB, kg) and height (HT, m), and the distance from the closest biosolids trench

Error source	DF	ALB, kg	HT, m
		-----P-value-----	
Treatment	7	0.0007	<0.0001
Distance from the trench, m	1	0.9451	0.8899
Distance from the trench*treatment	3	0.0150	0.0004

Table 6-7. Adjusted means for treatment effect on ALB, kg at different distances from the DRI biosolids using lsmeans statement in proc GLM.

Treatment	P-value <sup>†</sup>	Distance from the closest biosolids trench, m				
		3	6	12	15	18
Control	0.3463	2.28 a*	2.12 a		1.69	1.56
168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	0.0106	1.39 b	-	3.02	-	-
337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	0.1530	1.54 ab	1.85 a			
504 kg N ha <sup>-1</sup> yr <sup>-1</sup>	0.0163	1.25 b	0.89 c			

\*Treatments with the same letter in columns are not significantly different (P=0.05).

<sup>†</sup>P-value indicates significance of the distance from the DRI biosolids effect on the aboveground biomass.

Table 6-8. Adjusted means for treatment effect on the tree height (HT), m at different distances from the DRI biosolids using lsmeans statement in proc GLM.

Treatment	P-value	Distance from the closest biosolids trench, m				
		3	6	12	15	18
Control	0.0742	4.5 a	4.4 a	-	4.0	3.9
168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	0.0004	3.6 b	-	4.7	-	-
337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	0.5187	3.6 b	3.8 b	-	-	-
504 kg N ha <sup>-1</sup> yr <sup>-1</sup>	0.1236	3.5 b	3.1 b	-	-	-

\*Treatments with the same letter in columns are not significantly different (P=0.05).

<sup>†</sup>P-value indicates significance of the distance from the DRI biosolids effect on the tree height.

Table 6-9. Carbon, N and P concentrations in the hybrid poplar biomass.

Element	Aboveground leafless biomass	Stumps and roots	References
C, %	50	50	(Zabek and Prescott, 2006; Fang et al., 2007)
N, mg g <sup>-1</sup>	8.9-9.2	16.5±0.89 <sup>1</sup>	(Heilman and Stettler, 1986; Pregitzer et al., 2000), Kostyanovskiy, unpublished data
P, mg g <sup>-1</sup>	1.24-1.36	2.7-2.9	(Heilman and Stettler, 1986), Kostyanovskiy, unpublished data

<sup>1</sup>±SE

Table 6-10. Biomass production and C, N, and P storage in the 2 year old hybrid poplar plantation.

Treatment		Belowground biomass	Total biomass	C, total	N, total	P, total
		-----Mg ha <sup>-1</sup> -----			-----Kg ha <sup>-1</sup> -----	
Control	ab*	1.16±0.17	4.21±0.63	2.11±0.31	47±7	7.2±1.1
168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	ab	1.14±0.20	4.14±0.71	2.07±0.36	46±8	7.1±1.2
337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	b	0.92±0.16	3.36±0.57	1.68±0.28	37±6	5.7±1.0
504 kg N ha <sup>-1</sup> yr <sup>-1</sup>	c	0.47±0.34	1.71±0.12	0.85±0.06	19±1	2.9±0.2
AD 45 cm	b	1.56±0.22	5.65±0.80	2.82±0.40	62±9	9.7±1.4
AD 90 cm	ab	1.76±0.30	6.40±1.07	3.20±0.54	71±12	11.0±1.8
LS 45 cm	ab	1.62±0.20	5.88±0.73	2.94±0.36	65±8	10.1±1.2
LS 90 cm	abc	0.85±0.10	3.08±0.37	1.54±0.19	34±4	5.3±0.6

\* Treatments with the same letter in columns are not significantly different (P=0.05).

Table 6-11. Leaching rates of total N (NO<sub>3</sub>-N and TKN), and total P from the hybrid poplar–DRI biosolids and conventional fertilization study over the two years of tree growth (July 2006–October 2008).

Treatment	Total N	Total P
-----Leaching rates, kg ha <sup>-1</sup> -----		
Control	4.0±1.9 b	0.04±0.01 c
168 kg N ha <sup>-1</sup> yr <sup>-1</sup>	31.1±13.3 b	0.05±0.01 c
337 kg N ha <sup>-1</sup> yr <sup>-1</sup>	28.5±9.3 b	0.04±0.01 c
504 kg N ha <sup>-1</sup> yr <sup>-1</sup>	17.8±4.9 b	0.04±0.01 c
AD 45 cm	232.0±47.5 a	0.13±0.01 b
AD 90 cm	443.9±182.7 a	0.44±0.14 ab
LS 45 cm	419.7±176.3 a	0.17±0.06 b
LS 90 cm	701.8±356.5 a	0.52±0.14 a

\*Treatments in each column followed by the same letter are not significantly different (P=0.05).

Table 6-12. Predicted biomass production, C, N and P storage in the 6 year old hybrid poplar plantation in DRI biosolids.†

Treatment	Aboveground biomass	Belowground biomass	Total biomass	C total	N, shoots	N, total	P, shoots	P, total
	-----Mg ha <sup>-1</sup> -----				-----Kg ha <sup>-1</sup> -----			
LS biosolids at 383 Mg ha <sup>-1</sup>	22.1	8.4	30.5	15.3	200	339	29	53

†Values are based on the average dry weight of Hybrid Poplar plantation of tree density 1077 trees ha<sup>-1</sup>, grown on the DRI biosolids in Maryland at the 6 year of growth (Felix et al., 2008), and average elemental concentrations (Table 9).



## FIGURES

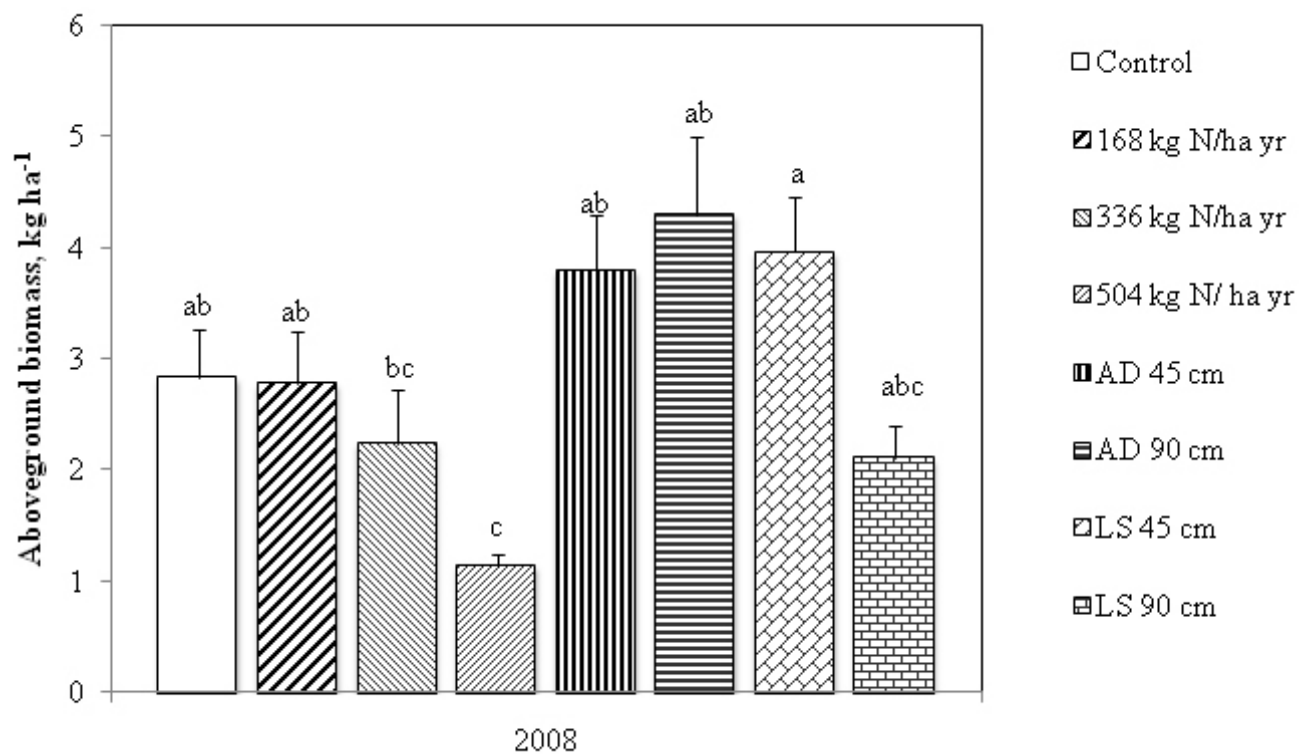


Figure 6-1. Aboveground biomass production for two year old hybrid poplar plantation treated with conventional fertilizer and DRI biosolids. Error bars represent SE. Treatments with the same letters are not significantly ( $P=0.05$ ) different.

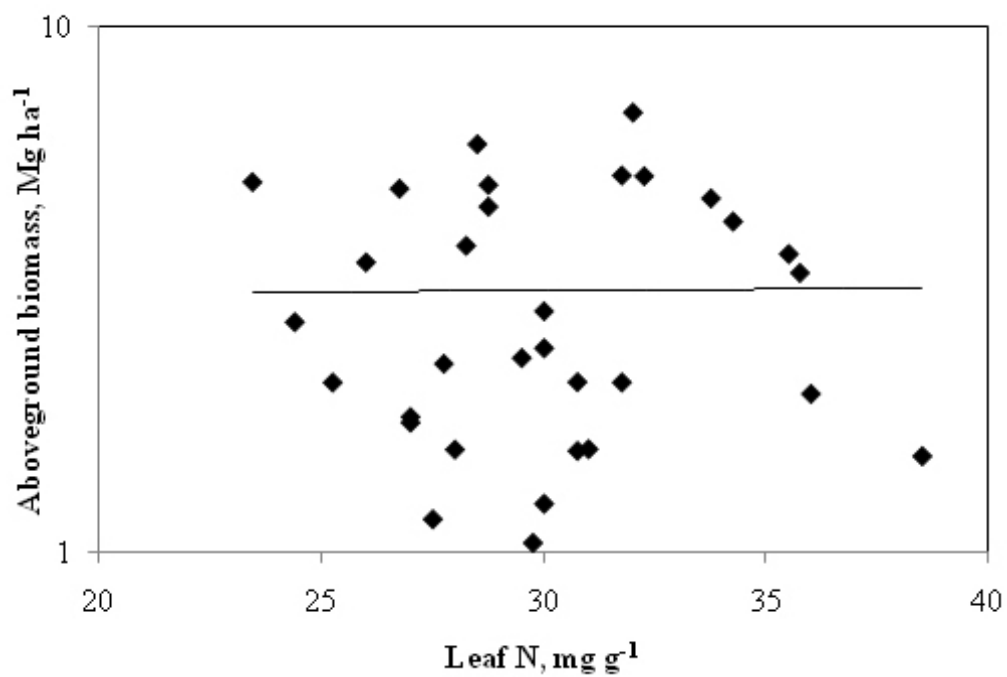


Figure 6-2. Relationship between log transformed aboveground biomass and foliar N concentrations during the second growing season (2008). Each point is an average at each block of each treatment.  $\text{Log } y = 0.001x + 0.988$  ( $R^2 = 0$ ,  $P = 0.9706$ ).

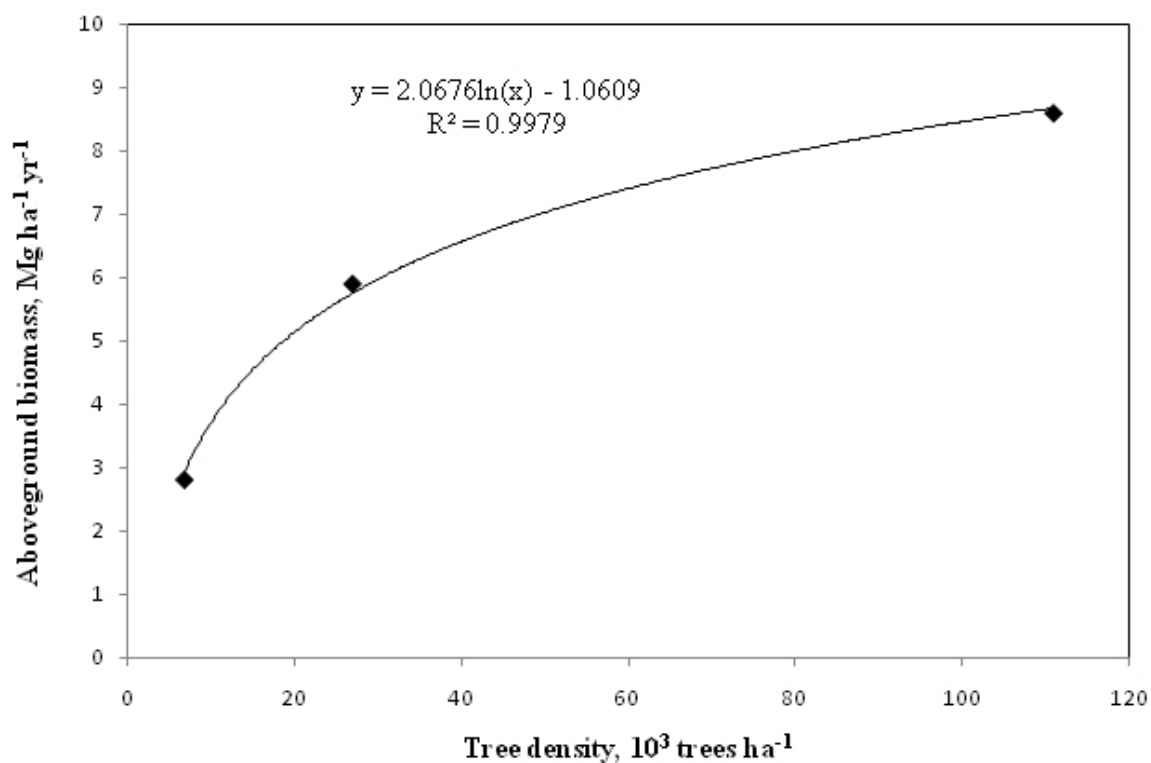


Figure 6-3. Aboveground leafless biomass of Poplar versus tree density at the second year harvest (Heilman and Peabody, 1981). Logarithmic function suggests linear increase in aboveground biomass with increasing tree density in the lower part of the curve.

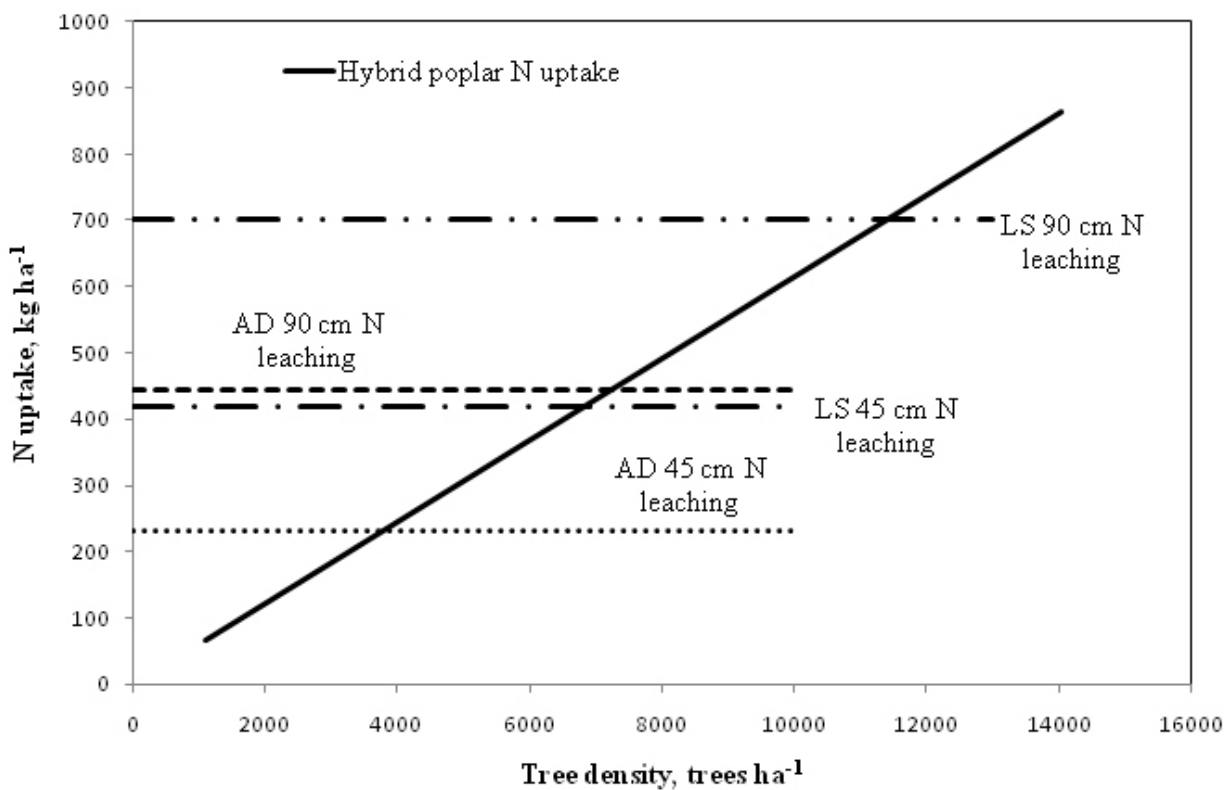


Figure 6-4. Hybrid poplar tree density, required to uptake the N, which otherwise was lost into groundwater from the DRI biosolids. Horizontal lines represent the mean values of N loss to the groundwater from the DRI biosolids treatments between July 2006 and October 2008.

## CHAPTER 7

### SUMMARY and CONCLUSIONS

Deep row incorporation (DRI) technology is a recognized biosolids recycling technique for surface mined land reclamation sites (Taylor et al., 1978; Kays et al., 1997; Felton et al., 2008) as is a cost effective method for bioenergy crops production (Felix et al., 2008). For this reason, the DRI is utilized to restore productivity of surface mined soils and as an amendment for short-rotation poplar plantations (Kays et al., 1997; Kays et al., 2000).

There is potential to establish highly productive, short-rotation forestry systems and enhance P and organic C in the mine soils by employing the DRI. The biosolids DRI for hybrid poplar production in the mid-Atlantic Coastal Plain mineral sand mining reclamation site, characterized by coarse-textured soils overlying shallow groundwater, was intended to determine the boundary conditions for this biosolids recycling method.

### Leaching of N and P

The purpose of this objective was to compare the effects of DRI biosolids type and annual conventional fertilizer applications on N and P leaching losses from a hybrid poplar stand established in a coarse-textured mineral sand mine reclamation site.

We found that N leaching from both AD and LS biosolids originally occurred mostly as  $\text{NH}_4\text{-N}$  and organic N, which forms combined to represent about 50% of the N leached. Further N leaching mostly occurred as  $\text{NO}_3\text{-N}$ . There was no significant difference in the amount of N forms leached between the biosolids type and rate treatments; however, the mean values of  $\text{NO}_3\text{-N}$ ,  $\text{NH}_4\text{-N}$  and TKN leached were highest for the LS 90 cm treatment, which received the highest

N rate among the DRI biosolids treatments. The amount of N lost from the DRI biosolids via leaching as detected by zero tension lysimeters in July 2006-December 2008 was 261–803 kg N ha<sup>-1</sup>, which was roughly 3% of the N applied. This value is 40% of the leaching rates from the land applied biosolids at the rate of 134 Mg ha<sup>-1</sup> (Stehouwer et al., 2006). The amount of N leached from the DRI biosolids also exceeded the optimum N uptake rates by the 2 year old hybrid poplar plantation planted at the density of 10000 trees ha<sup>-1</sup> by 2.3-4.8 times (Hansen et al., 1988) as N was lost to the groundwater unreclaimed by the vegetation. Despite the high concentrations of NO<sub>3</sub>-N, NH<sub>4</sub>-N and TKN in the leachate from the fertilizer treatments, the leaching rates were not significantly different from the unfertilized control and were significantly lower than from the biosolids treatments.

We also determined that the biosolids DRI at these rates decreased pH in the vadose zone under the biosolids seams due to extensive nitrification. Entrenched biosolids possessing high P-binding capacity posed little risk of P leaching through the coarse-textured soils with poor P retention into groundwater. Deep row entrenching of biosolids in coarse-textured media should not be employed as a mineland reclamation technique because the anaerobic conditions required to reduce mineralization and nitrification cannot be maintained in such permeable soils.

### **Temporal and Spatial Changes in C, N and P**

The purpose of this objective was to determine the effects of aging on the N, C and P dynamics in the DRI biosolids seams by measuring the changes in net masses of biosolids C, N, and P retained in the seams after two years of entrenchment.

Organic C level decreased by 40% in the LS biosolids seams compared to 25% in the AD seams, likely due to increase in labile organic matter susceptible to mineralization in the alkaline

LS biosolids (Curtin et al., 1998). Both AD and LS biosolids seams lost about 50% of total N over the course of 2 years. Concentrations of  $\text{NO}_3\text{-N}$  were higher in the AD, while  $\text{NH}_4\text{-N}$  was higher in the LS biosolids seams. Close to 90% of N lost from the DRI biosolids seams was either lost to denitrification as  $\text{N}_2\text{O}$  or  $\text{N}_2$  ammonia volatilization, or leached into groundwater unaccounted by zero tension lysimeters. Most of the AD biosolids P was complexed in Al and Fe forms, and P in the LS seams was Ca-associated. We did not detect significant P losses from the DRI biosolids; however, there was significant translocation of P towards the lower parts of the lime stabilized DRI biosolids seams. This was attributed to the colloidally-facilitated transport of organic P and mineralization of the upper parts of the LS seams. Labile P decreased with decrease in organic C in the AD and LS biosolids seams, which indicated that P leaching potential from the DRI biosolids decreased with aging.

Our data showed that anaerobic conditions were not prevalent enough within the biosolids seams to maintain the low N mineralization and nitrification and C decomposition rates needed to prevent N and C loss. The biosolids rate for environmentally sound deep row incorporation in coarse textured soils should be based on crop N requirements and N mineralization considerations. There was no evidence that the DRI biosolids treated with Al and Fe salts or lime will result in P loss.

### **Greenhouse Gas Emissions**

While the DRI biosolids technology has been shown to be beneficial for hybrid poplar growth and biomass production (Felix et al., 2008), greenhouse gas dynamics and effects of the DRI biosolids GHG emissions on climate radiative forcing are not clear. The purpose of this research was to compare the effects of various DRI biosolids types and conventional N

fertilization on N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> emissions. We also determined the influence of location in the biosolids seam on N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> emissions.

Our results suggested that N<sub>2</sub>O is the dominant greenhouse gas emitted from the DRI biosolids examined in this study. Fluxes of N<sub>2</sub>O were influenced by the biosolids pH, and had strong seasonal dynamics, increasing during the summer periods. Conventional N fertilization did not result in significantly higher global warming potential (GWP) than the unfertilized control, as its effect may have been masked by the elevated N<sub>2</sub>O emissions due to N groundwater leaching from adjacent DRI biosolids. The contributions of CH<sub>4</sub> and CO<sub>2</sub> to the GWP were small. Expressed as global warming potentials for the period of October 2006 to December 2008, N<sub>2</sub>O emissions from AD treatments (equivalent to 101.5 Mg C ha<sup>-1</sup>) were 4.6 times higher than from LS and 14.5-16.1 times higher than from the fertilizer treatments. Thus, AD biosolids offset most of the C sequestration gains from the DRI biosolids (Li et al., 2005). Deep row incorporation of lime stabilized biosolids posed a lower risk of N<sub>2</sub>O emissions than anaerobically digested biosolids.

### **Biomass Production, C, N and P Sequestration by Hybrid Poplar**

Previous studies on DRI biosolids–hybrid poplar plantations demonstrated high tree biomass productivity of poplars within six years of growth but did not explicitly measure poplar uptake of N and P from the biosolids (Felix et al., 2008). We conducted this study to investigate the effects of DRI on poplar biomass dynamics, C sequestration, and N and P uptake in order to assess the potential of hybrid poplar to offset possible environmental effects from the DRI.

We found that the amount of C sequestered by the trees reached its highest values of up to 3.20±0.54 Mg ha<sup>-1</sup> in the AD 90 cm and LS 45 cm treatments, which were not significantly



different from the control or the  $168 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  treatment of  $2.07 \pm 0.36$  to  $2.11 \pm 0.31 \text{ Mg ha}^{-1}$ . Nitrogen and P storage in the tree biomass followed similar patterns, attaining maxima of  $71 \pm 12 \text{ kg N ha}^{-1}$  and  $11.0 \pm 1.8 \text{ kg P ha}^{-1}$ , respectively. Our results suggested that the DRI biosolids provide a favorable environment for growth and development of hybrid poplar when compared with the similar rates of conventional fertilizer; however, they present several drawbacks. Such drawbacks include reduced biomass production and nutrient uptake by the trees grown the highest rate of lime stabilized DRI biosolids, possibly as a result of impeded root growth at the initial development stages. Significant loss of N into groundwater due to biosolids N mineralization rate greatly exceeding tree N uptake rate poses a serious water quality issue in the coarse-textured soils. Although EPA permits higher than required biosolids application rates for the purpose of achieving the reclamation goals at mineland sites (Haering et al., 2000), annual N losses to the groundwater comparable with the N uptake levels for the six year rotation are likely to result in significant damage to the local groundwater quality and, therefore, should be avoided by decreasing the biosolids entrenchment rates and increasing tree planting density.

### **Implications of the Research**

Findings of this research provide a number of environmental implications. The research provides a quantitative estimate of C, N and P transformations in the DRI biosolids at the coarse-textured mineland reclamation site within two years of establishment. Adoption of the biosolids DRI can result in detrimental effects on groundwater quality and contribute to global warming, if applied to coarse-textured soil environment.

The leaching of N is an important issue for biosolids applications exceeding the agronomic N rates (Haering et al., 2000). This research shows that in coarse-textured soils high

N leaching occurs regardless of the DRI biosolids application rate or treatment process.

Precipitation in the mid-Atlantic Coastal Plain exceeds evapotranspiration by 20% (Sun et al., 2002; Lu et al., 2003), and percolate is likely to transport dissolved N from the DRI biosolids into groundwater. Soil physical properties and depth of the groundwater table should be taken into account at the DRI biosolids recycling sites.

In an attempt to protect water quality in agricultural watersheds the Unified National Strategy for Animal Feeding Operations (USDA/USEPA, 1999) required each state National Resources Conservation Service (NRCS) to address P nutrient management standards. Various P indexing approaches were adopted by most states; however, they haven't been objectively validated for biosolids and may result in additional restrictions on the biosolids recycling programs (Elliott et al., 2006; Elliott and O'Connor, 2007). This research offers evidence that P leaching from the anaerobically digested and lime stabilized DRI biosolids is negligible, and P leaching potential from the DRI biosolids decreases with aging. It also shows that in the extreme case of the biosolids application rates exceeding the plant N and P requirements by two orders of magnitude the total P leaching from the biosolids is only 0.2–0.5 kg P ha<sup>-1</sup>.

Biosolids entrenchment increases soil C, but also results in high N<sub>2</sub>O emissions which are able to offset most of the C gains in terms of global warming potential (IPCC, 2007). Therefore, the DRI might not be used to offset anthropogenic CO<sub>2</sub> emissions.

It is important to recognize the role of hybrid poplar as a sink of nutrients in the DRI biosolids system. The fast growth and ability to sequester N are the primary reasons for hybrid poplar use in the DRI biosolids technique (Kays et al., 1997; Felix et al., 2008). Special consideration should be given to the planting density, and our data clearly illustrates that 1077 trees ha<sup>-1</sup> is not sufficient to prevent the N leaching. More research is needed in order to develop

effective methods for determining planting density requirements based on the DRI biosolids rates.

The biosolids DRI is a recognized method for biosolids recycling, especially for production of fast-growing bioenergy crops, but detrimental effects on water and air quality should be carefully considered in its implementation.

### **Future Research**

The key questions that require investigation on the biosolids DRI are: (i) how do soil physical-chemical characteristics (e.g., texture, permeability, cation exchange capacity) affect N transformations in the biosolids seam and N leaching?; (ii) How does biosolids aging affect long-term (e.g., 10-20 years) P leaching potential from the DRI biosolids?; (iii) How does the biosolids treatment process (e.g., lime stabilization, anaerobic digestion, aerobic digestion, composting) influence greenhouse gas emission and C sequestration potential of the DRI biosolids? Future research should address these issues in order to provide critical information for the biosolids recycling managers to help them make environmentally safe decisions.

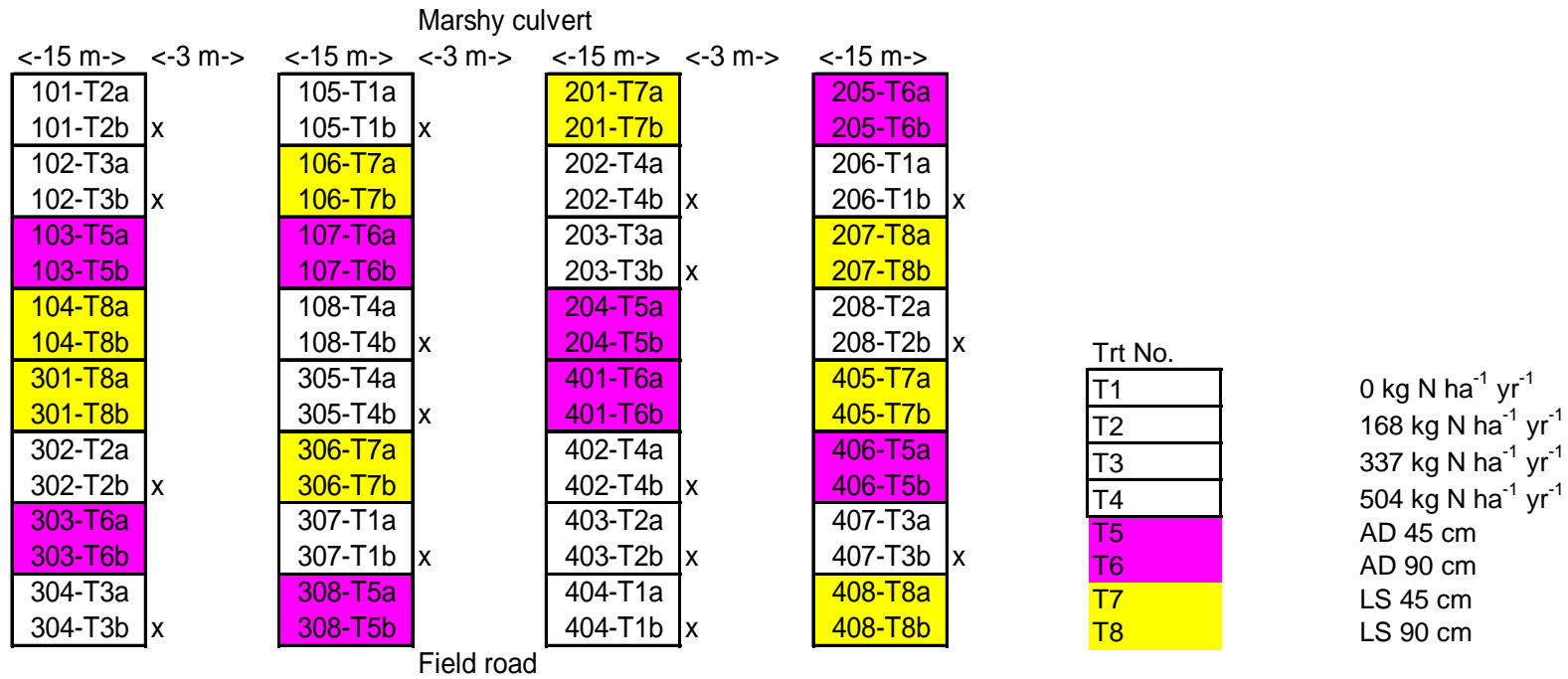
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APPENDIX

Appendix A. Deep row incorporated biosolids-hybrid poplar experiment map.<sup>1</sup>



<sup>1</sup> 3-digit numbers are plot numbers, with first digit representing block number and third digit reflecting the order of treatment in each block. 1-digit numbers following the "T" are treatment codes. Letters 'a' and 'b' next to the treatment codes indicate tree rows. 'x'-s indicate rows with zero tension lysimeters installed in conventional fertilizer plots.

**Appendix B. Individual pH, EC, DO, N and P forms in leachate collected from zero tension lysimeters over the study period (July 2006-December 2008).**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>	
7/14/2006	1	105-T1b	8.18	0.835		1320	18.95074	0	1.318459	0.026722	0.232116	
	2	206-T1b	8.03	0.877		1200	20.62931	0	1.850148	0.007383	0.325127	
	4	404-T1b	8.15	0.664		380	8.139619	1.161418	3.410785	0.010854	0.21838	
	5	101-T2b	8.8	0.791		1820	11.43018	0	1.724581	0.007383	0.252529	
	6	208-T2b	8.08	1.074		710	41.83652	0	1.572636	0.012338	0.149298	
	7	302-T2b	7.89	0.635		950	3.22881	0	1.653794	0.007383	0.158434	
	8	403-T2b	7.65	0.8		1770	18.61803	0.142445	1.876732	0.007383	0.164606	
	9	102-T3b	7.82	0.716		560	6.65915	0	1.864493	0.007383	0.141898	
	10	203-T3b	7.99	0.869		1020	11.47875	0	2.020539	0.007383	0.149298	
	11	304-T3b	7.97	0.697		1000	4.030528	0.130975	1.125582	0.007383	0.1904	
	13	108-T4b	8.2	1.3		830	43.29668	0	1.722052	0.03073	0.117291	
	14	202-T4b	7.92	0.778		1240	19.96648	0.010191	2.123781	0.007383	0.117291	
	15	305-T4b	8.4	0.892		710	12.03595	0	2.119977	0.013258	0.189849	
	16	402-T4b	7.98	0.953		590	25.85348	0	1.642133	0.011768	0.15953	
	22	308-T5b	6.46	1.762		1150	0.236213	117.0475	136.9461	0.047545	0.95629	
	27	205-T6a	7.33	0.828		4200	0.718093	15.18587	19.63536	0.039119	0.221083	
	28	205-T6b	7.01	0.646		13000	4.486743	0.473818	2.446918	0.007383	0.190297	
	8/10/2006	5	101-T2b	8.53	0.628		780	9.92557	0	0.93386	0.01191	0.117291
		9	102-T3b	7.97	0.708		420	8.34999	0	1.757577	0.012757	0.150638
15		305-T4b	8.16	1.227		360	41.07942	0.0233	6.72984	0.014872	0.152609	
19		204-T5a	7.69	1.01		430	0.184223	8.498636	14.21136	0.007383	2.645632	
20		204-T5b	7.77	0.814		1700	0.000048	6.291341	11.07056	0.041476	0.117291	
25		107-T6b	7.94	0.925		310	1.015622	1.132934	3.822254	0.024915	0.963457	
27		205-T6a	8.23	2.79		340	0.008433	289.6847	471.0303	0.027074	0.117291	

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
8/10/2006	28	205-T6b	8.09	1.16		340	0.088125	91.8143	118.7002	0.043965	0.188269
	31	401-T6a	7.64	12.22		550	0.020268	56.20224	80.58006	0.029435	0.14362
	32	401-T6b	7.55	0.895		230	0	36.05423	22.97456	0.039182	0.162194
	34	106-T7b	8.65	0.679		460	3.102318	0	1.473197	0.007383	0.149291
	35	201-T7a	8.63	0.489		740	2.489354	3.75653	7.618391	0.007383	0.227653
	37	306-T7a	8.27	0.888		430	12.17796	3.801226	7.242947	0.019014	0.243384
	46	301-T8b	7.5	0.593		1710	10.35415	0.288713	2.096161	0.007383	0.191366
9/8/2006	2	206T1b	8.07	0.756		9995	15.11067	1.461758	3.556416	0.038226	0.13451
	4	404-T1b	8.44	0.597		9995	8.368778	14.98542	20.56797	0.041923	0.13451
	6	208-T2b	8.08	1.289		9995	89.25045	12.29946	6.42954	0.025815	0.296852
	17	103-T5a	7.88	2.27		9995	2.541058	149.9914	364.2351	0.015832	0.13575
	18	103-T5b	7.92	2.38		9995	0.317994	153.6279	312.979	0.007383	0.172927
	19	204-T5a	8.08	0.964		9995	0.047268	13.37295	18.3407	0.007383	0.139448
	20	204-T5b	7.7	0.856		9995	4.363159	12.26623	21.80417	0.032026	0.142503
	21	308-T5a	5.85	0.698		9995	3.275683	16.49127	25.35419	0.039377	0.117291
	22	308-T5b	8.14	2.32		9995	0.031355	178.0833	424.3357	0.015609	0.117291
	23	406-T5a	7.84	1.63		9995	28.07643	96.34053	133.8912	0.007383	0.152185
	24	406-T5b	7.72	3.74		9995	274.7868	183.2356	429.8214	0.062006	0.163459
	25	107-T6a	7.66	0.959		9995	0.291126	4.227313	7.271753	0.007383	0.224749
	26	107-T6b	8.03	0.915		9995	0.027173	1.563494	4.153232	0.007383	0.143104
27	205-T6a	7.99	2.54		9995	0.047641	249.5497	482.8199	0.03374	0.150551	
28	205-T6b	8.2	0.919		9995	0.115964	64.97495	70.60045	0.007383	0.210789	
29	303-T6a	8.13	3.39		9995	0.051725	342.6039	439.0368	0.007383	0.202813	
30	303-T6b	6.76	0.867		9995	0.033423	13.87149	19.87877	0.041153	1.80459	



**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>	
9/8/2006	31	401-T6a	7.61	1.236		9995	0.016559	65.09341	83.64112	0.007383	0.117291	
	32	401-T6b	7.16	0.773		9995	1.627006	21.58924	34.12628	0.007383	0.142928	
	33	106-T7a	8.44	11.76		9995	0	457.3203	2573.598	0.168016	0.151928	
	34	106-T7b	7.91	4.22		9995	380.7769	376.1696	543.7267	0.009927	0.153103	
	35	201-T7a	8.09	1.117		9995	7.242892	97.47011	114.4185	0.007383	0.19538	
	36	201-T7b	8.23	2.11		9995	32.30981	119.674	342.6765	0.022091	0.196116	
	40	405-T7b	7.77	4.85		9995	933.0027	10.13771	156.1245	0.108736	0.141864	
	41	104-T8a	8.34	12.84		9995	0.042096	454.0309	2789.006	0.189526	0.196025	
	42	104-T8b	7.43	2.6		9995	150.799	192.9181	78.59493	0.017881	0.199687	
	43	207-T8a	8.14	4.99		9995	435.5817	538.9177	643.5064	0.064876	0.214763	
	44	207-T8b	7.53	0.896		9995	0.210848	59.60327	61.60162	0.007383	0.172048	
	45	301-T8a	7.38	1.334		9995	0.067828	83.77174	99.5858	0.007383	1.586911	
	46	301-T8b	7.09	0.578		9995	8.056841	1.656939	4.815237	0.007383	1.599259	
	47	408-T8a	8.12	3.29		9995	311.4569	286.1994	543.0533	0.026547	0.13584	
	48	408-T8b	8.35	1.702		9995	129.3647	92.51428	100.1394	0.007383	0.136127	
	10/6/2006	1	105-T1b	7.56	0.796		2843	0.198189	9.653392	16.44061	0.007383	0.117291
		2	206-T1b				2843	16.49887	2.051341	2.625779	0.007383	0.138688
		3	307-T1b	7.54	0.754		2843	2.803363	0.447651	1.815338	0.038147	0.156234
4		404-T1b	8.25	0.567		2843	7.81677	4.172784	7.062573	0.007383	0.15001	
17		107-T5a	7.87	2.85		2843	0.057553	264.5195	529.1199	0.007383	0.130972	
18		107-T5b	7.88	3.48		2843	0.093907	365.8859	648.2529	0.007383	0.137881	
19		204-T5a	7.83	1.028		2843	16.86731	21.2018	40.85788	0.013828	0.147701	
20		204-T5b	7.96	1.05		2843	0.108216	14.20902	23.67002	0.036707	0.222427	
21		308-T5a	6.55	0.79		2843	0.058786	27.46967	54.23461	0.042565	0.157535	
22		308-T5b	7.79	2.13		2843	0.080302	29.5047	282.9493	0.017555	0.146132	

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
10/6/2006	23	406-T5a	7.76	1.636		2843	9.103019	41.47506	106.5181	0.02621	0.190995
	24	406-T5b	7.58	2.81		2843	21.88927	27.85068	285.8883	0.007383	0.192284
	25	107-T6a	7.58	1.066		2843	0.076	11.55439	21.28341	0.03858	0.318796
	26	107-T6b	7.83	1.048		2843	8.524056	9.550918	18.7485	0.007383	0.16028
	27	205-T6a	7.56	2.66		2843	0.15066	41.55706	511.9068	0.035448	0.226737
	28	205-T6b	7.28	1.037		2843	1.104747	56.98971	62.64331	0.035792	0.13648
	29	303-T6a	7.99	2.39		2843	0.044609	34.52833	405.8335	0.035231	0.137699
	30	303-T6b	7.49	1.96		2843	0.039143	22.25147	295.666	0.029487	0.142661
	32	401-T6b	7.33	0.925		2843	0.470152	30.83313	67.86008	0.026961	0.117291
	33	106-T7a	8.48	10.41		2843	1.154532	437.8614	1141.737	0.201146	0.265222
	34	106-T7b	8.24	2.44		2843	170.0408	126.5893	285.2442	0.038693	0.268824
	35	201-T7a	7.99	1.938		2843	9.895554	66.16052	317.167	0.026123	0.137881
	36	201-T7b	8.5	1.981		2843	40.98502	53.97631	263.8984	0.027014	0.130086
	37	306-T7a	7.41	6.49		2843	95.0571	66.76582	635.3668	0.024871	0.148495
	38	306-T7b	6.72	1.758		2843	44.60974	32.23924	33.30043	0.031208	0.154609
	39	405-T7a	7.6	4.78		2843	59.97629	45.62717	366.8278	0.007383	0.15001
	40	405-T7b	8.06	3.67		2843	63.80649	11.19786	71.61084	0.007383	0.150291
	41	104-T8a	8.84	13.46		2843	7.178683	472.1805	557.3399	0.289115	0.164057
	42	104-T8b	7.99	6.02		2843	294.1813	785.7458	1034.412	0.067849	0.117291
	43	207-T8a	8.31	3.77		2843	23.27674	50.2403	629.258	0.007383	0.130402
	44	207-T8b	8.29	1.924		2843	1.079549	25.5292	325.3564	0.035128	0.139432
	45	301-T8a	7.92	2.66		2843	0.199277	37.54116	480.0357	0.037828	0.13188
	46	301-T8b	6.72	0.584		2843	9.454345	2.263541	4.504064	0.037589	0.131138
	47	408-T8a	7.83	1.605		2843	41.34243	44.91642	112.0932	0.035734	0.117291

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
10/6/2006	48	408-T8b	8.17	0.529		2843	10.15456	26.43908	50.44465	0.032149	0.148124
11/3/2006	1	105-T1b	7.61	0.804		550	14.4416	0.587794	1.059564	0	0.065077
	2	206-T1b	7.58	1.025		750	41.72104	1.332553	0	0	0.048981
	3	307-T1b	7.69	0.779		440	2.227788	0.341947	1.069447	0	0.058417
	4	404-T1b	7.84	0.604		220	6.407507	0.939989	1.339905	0.00216	0.056534
	17	103-T5a	7.92	2.72		1250	0.14297	49.63581	406.4766	0.019349	0.571964
	18	103-T5b	8.07	3.46		900	0.163078	382.3437	460.6686	0.002503	0.707677
	19	204-T5a	7.72	1.07		2380	0.89212	11.72553	17.00623	0	0.041662
	20	204-T5b	7.37	1.06		5620	12.33087	20.40121	25.04162	0.001138	0.049604
	21	308-T5a	6.5	0.704		1075	1.91E-04	26.58119	32.22174	0	0.036545
	22	308-T5b	7.74	2.15		725	0.15864	195.2223	297.4217	0	0.139934
	23	406-T5a	7.64	1.508		2060	5.03677	71.41325	101.9243	0.001154	0.049509
	24	406-T5b	7.62	2.82		450	158.8884	164.5468	206.4395	0.014897	0.084655
	25	107-T6a	7.65	1.218		2340	0.563404	33.16115	44.98696	0.011084	0.034947
	26	107-T6b	7.82	1.024		450	0.13878	8.308674	12.45158	0	0.060729
	27	205-T6a	7.81	3.18		875	0.232506	356.1834	419.28	0.001845	0.191109
	28	205-T6b	7.76	1.137		3620	42.16614	53.46099	63.2502	1.100749	4.098653
	29	303-T6a	7.61	2.48		2015	0.167069	210.9605	386.2963	0.011623	0.22806
	30	303-T6b	7.34	1.601		6100	0.161503	118.8074	183.9124	0	0.270546
	31	401-T6a	7.81	1.452		550	0.100284	99.09049	144.4619	0	0.076685
	32	401-T6b	6.98	0.863		2370	0.552285	40.709	54.24818	0	0.042727
	33	106-T7a	8.47	10.09		290	0.526988	1282.116	1338.481	0.360973	0.706735
	34	106-T7b	7.78	2.3		10635	68.16969	167.8024	241.8476	0.016044	0.090323
	35	201-T7a	7.87	1.56		1545	4.818871	133.8649	204.7984	0.019263	0.049616
	36	201-T7b	8.51	1.392		1785	14.41064	124.3143	173.0385	0.003911	0.037202

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>	
11/3/2006	37	306-T7a	6.94	6.79		2275	346.291	223.1674	297.3442	0.006736	0.042744	
	38	306-T7b	6.76	1.86		550	147.4634	44.69935	28.18524	0.00697	0.057734	
	39	405-T7a	7.76	4.57		1360	340.5705	252.8878	366.4684	0.034978	0.078889	
	40	405--T7b	7.75	3.09		3880	319.514	67.2096	24.5541	0.099661	0.091998	
	41	104-T8a	8.26	12.9		350	1.686884	1826.548	2024.493	1.1165	1.515433	
	42	104-T8b	8.12	5.27		865	220.7731	339.0737	672.484	0.058915	0.39272	
	43	207-T8a	8.33	2.97		3540	134.0052	237.8674	425.3713	0.02006	0.462158	
	44	207-T8b	7.97	1.828		6600	1.788347	183.9655	313.9046	0.004819	0.284499	
	45	301-T8a	8.16	2.56		360	0.183557	233.6914	424.0995	0.004181	0.388036	
	46	301-T8b	6.72	0.537		6655	10.33514	3.731414	3.338341	0.003319	0.045195	
	47	408-T8a	7.54	1.479		1530	79.45158	114.7118	155.0817	0.005197	0.05276	
	48	408-T8b	7.24	0.474		2600	19.98155	19.52508	21.63214	0.004846	0.052841	
	12/1/2006	1	105-T1b	7.87	0.756	3.11	380	27.85819	14.209	17.24746	0.003617	0.055702
		2	206-T1b	7.73	0.941	4.98	2820	86.84254	4.340752	0	0.001251	0.064248
3		307-T1b	7.84	0.728	4.52	300	2.981829	0.697633	1.305429	0.003509	0.048146	
4		404-T1b	8.05	0.512	5.22	120	5.859198	0.773735	1.114342	0.004343	0.066846	
17		103-T5a	7.82	1.924	6.47	1420	0.35236	187.4539	313.2405	0	0.113963	
18		103-T5b	8.36	2.76	4.28	675	1.074468	331.8959	389.8148	0.008742	0.188036	
19		204-T5a	8.01	0.657	3.77	11000	20.83778	16.89986	16.85075	0.003458	0.059791	
20		204-T5b	8.84	0.568	3.72	11370	12.22399	42.44329	57.1984	0.026639	0.051268	
21		308-T5a	6.78	0.495	4.21	1025	3.588018	21.39173	30.70308	0	0.040275	
22		308-T5b	8.22	1.654	3.98	1240	0.150415	163.3101	270.994	0.001207	0.314206	
23		406-T5a	8.15	1.037	4.26	2320	37.89231	44.85468	57.26942	0.035299	0.050916	
24		406-T5b	7.92	1.24	5.36	3500	80.91344	50.9283	53.95112	0.009367	0.058487	

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
12/1/2006	25	107-T6a	7.8	0.952	4.74	620	0.472669	62.72212	98.44198	0.025489	0.069739
	26	107-T6b	8.58	0.972	4.39	550	0.794143	9.466491	14.69635	0.005626	0.05194
	27	205-T6a	7.74	1.74	4.22	5530	0.290134	184.4653	312.296	0	0.088262
	28	205-T6b	8.06	0.679	4.66	3100	51.12499	30.25251	29.50646	0	0.060159
	29	303-T6a	8.31	1.819	3.3	1900	0.210439	176.0055	281.8363	0.001114	0.077073
	30	303-T6b	8.2	0.678	3.72	10000	1.370414	58.63924	84.46826	0	0.067647
	31	401-T6a	7.81	1.339	4.54	970	0.130038	93.73601	137.331	0	0.058582
	32	401-T6b	7.9	0.639	4.74	1750	1.358238	31.47146	46.2196	0	0.058947
	33	106-T7a	8.74	8.12	2.21	290	0.355987	1101.987	1566.362	0.172783	1.255242
	34	106-T7b	8.09	1.076	4.46	11060	20.23725	101.6191	160.4738	0.01358	0.092971
	35	201-T7a	8.93	0.495	3.79	500	10.01504	45.73301	64.35092	0.001689	0.038342
	36	201-T7b	8.51	0.374	4	11090	1.731456	25.74405	35.8626	0.001145	0.038338
	37	306-T7a	7.3	4.22	4.61	720	484.9401	267.3576	299.7904	0.0098	0.041827
	38	306-T7b	6.91	1.704	5.1	1290	168.9463	30.83804	20.04563	0.026022	0.069066
	39	405-T7a	8.31	1.335	4.34	11100	98.55225	84.75986	105.0924	0.026493	0.077118
	40	405-T7b	8.32	1.069	3.56	11040	77.33069	36.28459	27.67518	0.495825	0.994109
	41	104-T8a	8.31	12.64	0.35	220	0.266529	1647.318	1377.292	0.637883	1.632086
	42	104-T8b	8.21	4.26	4.5	1480	216.6234	299.6519	430.08	0.038831	0.180527
	43	207-T8a	8.74	0.587	3.86	11000	28.46329	41.97884	64.63028	0.004282	0.067106
	44	207-T8b	8.75	0.331	3.93	11100	0.205471	20.63609	29.207	0.00109	0.055718
	45	301-T8a	8.8	1.716	1.34	310	1.745488	222.3074	415.7166	0.012719	0.181743
	46	301-T8b	7.2	0.304	4.51	11000	5.87777	9.661552	13.36732	0.00504	0.081308
	47	408-T8a	8.13	0.932	4.3	2260	95.59055	43.29185	36.64942	0.004018	0.077342
	48	408-T8b	6.59	0.298	4.82	4090	23.39333	2.123927	0.212003	0.001867	0.072593

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
12/15/2006	1	105-T1b	7.63	0.721	6.1	290	33.73404	5.925266	5.993458	0.001821	0.002678
	2	206-T1b	8.5	0.803	7.61	410	60.36944	4.474917	0	0	0.017967
	3	307-T1b	8.45	0.612	7.44	170	3.759817	2.393074	2.813965	0.001617	0.01795
	4	404-T1b	8.15	0.511	7.68	150	5.840115	1.020072	1.76262	0.004928	0.014946
	17	103-T5a	8.12	2.05	5.01	400	0.246626	215.1902	283.7362	0.002286	0.014946
	18	103-T5b	9.09	2.26	8.17	210	1.241919	236.8796	481.2617	0	0.039189
	19	204-T5a	8.1	0.658	5.82	1225	16.63535	24.47582	23.82779	0.005144	0.002678
	20	204-T5b	8.33	0.726	4.85	2640	11.84457	60.8699	74.76288	0.004481	0.002678
	21	308-T5a	6.96	0.525	5.6	620	5.8846	23.73584	29.06512	0	0.16559
	22	308-T5b	8.01	1.449	6.12	320	0.215229	147.948	202.4671	0.00178	0.168403
	23	406-T5a	8.25	0.926	5.04	990	33.62594	38.40412	48.49478	0.005233	0.014427
	24	406-T5b	8.22	1.773	3.57	250	153.6807	81.086	61.77722	0.006337	0.014427
	25	107-T6a	8.66	0.881	5.89	150	0.211966	56.22648	78.0099	0	0.002678
	26	107-T6b	8.01	0.757	4.76	2950	0.196811	10.89844	13.3915	0	0.002678
	27	205-T6a	8.22	1	4.85	1346	0.246721	101.0016	140.6407	0	0.002678
	28	206-T6b	8.26	0.668	5.16	2490	31.096	21.39142	22.65449	0.004535	0.002678
	29	303-T6a	8.89	1.572	6.02	1100	0.056947	162.0816	244.2213	0	0.002678
	30	303-T6b	8.49	0.717	6.53	410	0.047716	59.3763	86.74162	0	0.002678
	31	401-T6a	8.7	1.289	6.88	560	0.434699	93.94628	140.8658	0	0.002678
	32	401-T6b	8.03	0.573	5.85	1650	1.154058	29.05986	31.4985	0	1.825836
	33	106-T7a	8.6	7.59	2.61	380	0.126841	663.1854	959.8144	0.159289	0.509399
	34	106-T7b	8.04	1.218	4.29	3000	2.804748	126.5732	175.5706	0.019097	0.019529
	35	201-T7a	9.2	0.267	6.58	2100	0.739158	12.65734	15.70936	0.001437	0.002678
	36	201-T7b	8.65	0.219	5.48	1000	0.363402	6.07548	8.4687	0	0.002678

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>	
12/15/2006	37	306-T7a	6.95	2.79	5.77	1350	331.3066	171.3276	163.6041	0.004813	0.002678	
	38	306-T7b	7.23	1.733	7.04	1000	162.7332	23.66688	10.48248	0.0011	0.002678	
	39	405-T7a	8.73	0.488	5.92	510	8.707172	25.53422	40.7008	0.012067	0.094086	
	40	405-T7b	8.76	0.98	4.48	700	16.83526	57.97268	92.79802	0.044332	0.098513	
	41	104-T8a	8.42	13.05	5.77	190	0.284195	799.3946	2573.279	0.931014	1.87577	
	42	104-T8b	8.48	3.78	6.33	315	185.2676	333.5446	446.1335	0.017722	0.025752	
	43	207-T8a	8.87	0.424	6	670	3.881488	24.1006	39.14018	0.001924	0.013469	
	44	207-T8b	8.25	1.505	4.34	680	0.092228	149.3829	319.3995	0.002507	0.126235	
	45	301-T8a	9.05	2.21	3.09	300	1.697383	229.4224	413.8223	0.00165	0.097854	
	46	301-T8b	7.29	0.28	4.3	1580	2.399289	13.39416	14.45097	0.001533	0.002678	
	47	408-T8a	8.1	1.402	5.05	710	133.8186	59.54028	62.89758	0.003667	0.002678	
	48	408-T8b	6.66	0.244	5.1	830	11.65322	1.054243	0.333051	0.008228	0.002678	
	1/5/2007	1	105-T1b	7.82	0.872	5.51	280	35.45462	2.480601	0	0.001587	0.002678
		2	206-T1b	8	0.859	5.59	560	57.55782	2.982075	0	0.001861	0.002678
3		307-T1b	7.71	0.733	6.4	260	3.733756	0.491992	0.80369	0.00413	0.002678	
4		404-T1b	8.7	0.572	7.11	190	5.770017	0.84282	0.832326	0.006167	0.015487	
17		103-T5a	7.87	1.766	6.53	760	3.143868	194.833	251.3149	0.001944	0.032432	
18		103-T5b	8.88	2.72	5.45	270	9.989018	287.1612	475.62	0	0.033574	
19		204-T5a	8.65	0.627	5.09	2050	16.00911	21.33054	28.34896	0.003353	0.002678	
20		204-T5b	8.32	0.686	4.57	3210	17.09424	48.77448	69.25262	0.002471	0.002678	
21		308-T5a	7.88	0.689	5.87	250	7.674019	39.104	62.11588	0	0.02456	
22		308-T5b	8.28	1.37	5.14	210	1.294472	121.8532	141.2955	0.001254	0.02456	
23	406-T5a	8.07	0.963	4.75	1500	32.4191	36.18796	48.969	0.009477	0.002678		
24	406-T5b	7.71	1.57	4.59	1050	115.7586	55.60342	59.93092	0.012883	0.382511		

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
1/5/2007	25	107-T6a	7.95	0.886	4.41	800	0.311883	49.48904	77.01932	0	0.002678
	26	107-T6b	7.89	0.624	4.72	9900	0.105028	7.89202	21.51778	0.001598	0.002678
	27	205-T6a	8.32	0.702	4.06	1600	0.088952	72.09934	122.8745	0	0.002678
	28	205-T6b	8.48	0.488	4.55	2880	16.88282	15.24186	13.64356	0.001643	0.486103
	29	303-T6a	8.26	1.328	6.31	960	0.547225	136.4959	251.4961	0	0.002678
	30	303-T6b	7.98	0.598	5.68	390	0.725776	47.6377	82.60882	0	0.002678
	31	401-T6a	8.53	1.15	5.47	700	0.126782	94.56804	158.975	0	0.002678
	32	401-T6b	7.42	0.414	5.88	2260	1.867453	17.80324	21.48609	0.00393	1.614465
	33	106-T7a	8.38	7.39	6.64	2360	0.39265	627.094	1166.051	0.095543	0.399605
	34	106-T7b	7.98	0.963	3.48	1350	48.87476	60.82822	101.5093	0.005654	0.012347
	35	201-T7a	8.84	0.266	4.77	2220	0.512871	11.2819	12.92705	0	0.012347
	36	201-T7b	8.31	0.242	4.3	2600	0.801641	6.239797	8.07334	0	0.002678
	37	306-T7a	6.12	2.81	6.86	740	323.5888	148.4329	177.6245	0.001906	0.002678
	38	306-T7b	6.69	1.441	6.64	3950	161.2817	15.8501	0	0	0.002678
	39	405-T7a	8.72	0.485	5.12	710	7.106157	27.08596	49.37056	0.009273	0.131587
	40	405-T7b	8.76	0.827	3.88	1890	25.29246	46.66834	0	0.183298	0.131789
	41	104-T8a	8.32	1.162	8.17	430	0.313456	790.296	2689.023	0.66041	1.659338
	42	104-T8b	8.28	2.91	6.7	440	175.4856	272.0174	400.5099	0.011005	0.016337
	43	207-T8a	8.08	0.481	3.73	3080	13.80397	21.75982	36.2381	0	0.031952
	44	207-T8b	8.5	0.925	3.17	270	0.425181	100.0617	223.6143	0.005323	0.031952
	45	301-T8a	8.64	1.961	3.63	450	0.221613	212.3818	429.5857	0.002668	0.033267
	46	301-T8b	6.69	0.273	5.4	5500	5.137183	13.11788	14.81563	0	0.002678
	47	408-T8a	7.4	0.98	5.06	650	96.26348	34.36192	16.66094	0.004083	0.002678
	48	408-T8b	6.5	0.184	7.32	1800	9.647477	0.41233	0.191008	0.004435	0.002678



**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
1/19/2007	1	105-T1b	7.46	0.924	3.87	670	20.29	0.99	0.162	2.81E-03	0.0213
	2	206-T1b	7.48	0.895	5.86	350	29.92	2.37	0.299	4.64E-03	0.0629
	3	307-T1b	7.88	0.709	9.34	190	4.25	1.68	2.1	5.99E-03	0.222
	17	103-T5a	8.15	1.781	5.48	1400	20.41	82.07	205	6.04E-03	0.0499
	18	103-T5b	8.68	2.52	2.7	670	19.54	60.08	260	1.25E-02	0.197
	19	204-T5a	7.26	0.715	5.38	1600	18.73	7.38	19	9.97E-03	0.00464
	20	204-T5b	7.14	0.825	3.28	4200	19.05	20.89	39.6	7.85E-03	0.0241
	21	308-T5a	6.52	0.52	5.91	480	18.93	11.07	22.5	7.74E-03	0.00239
	22	308-T5b	7.96	1.472	5.3	550	5.37	66.39	152	1.68E-03	0.234
	23	406-T5a	7.46	0.955	3.98	410	16.28	16.14	36.5	1.67E-02	0.038
	24	406-T5b	7.03	1.092	5.7	1135	41.45	54.42	29.8	1.75E-02	0.104
	25	107-T6a	7.46	0.799	2.68	7800	2.59	15.62	33.6	1.28E-03	0.0247
	26	107-T6b	7.5	0.513	5.15	1650	0.37	5.42	8.83	9.28E-04	0.0222
	27	205-T6a	7.44	0.87	3.95	4730	14.86	42.61	83.5	1.04E-03	0.129
	28	205-T6b	7.38	0.493	2.96	340	23.94	5.37	6.47	3.04E-03	0.0152
	29	303-T6a	8.64	1.021	4.57	250	3.89	49.64	135	1.73E-03	0.0548
	30	303-T6b	7.59	0.647	4.25	530	4.99	21.13	44.4	9.19E-04	0.0252
	32	401-T6b	6.67	0.364	4.29	1610	3.71	7.95	24.9	8.51E-04	0.0371
	33	106-T7a	8.67	4.9	9.1	1500	0.42	145.55	808	8.17E-02	0.964
	34	106-T7b	7.34	0.918	4.07	4800	29.61	29.61	60	1.02E-02	0.0198
	35	201-T7a	7.5	0.368	3.45	10770	1.75	4.95	15.3	6.76E-04	0.0093
	36	201-T7b	7.31	0.312	4.36	14000	0.96	3.89	6.42	0.00E+00	0.0257
	37	306-T7a	4.82	2.05	10.13	1400	106.42	43.00	71	1.36E-04	0.135
	38	306-T7b	6.8	1.572	8.89	3600	77.40	12.91	18	7.28E-04	0.146

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
1/19/2007	39	405-T7a	7.59	0.707	3.43	1650	8.01	12.14	26.1	1.99E-02	0.0802
	40	405-T7b	7.57	1.174	4.24	790	45.21	15.07	25.8	3.08E-01	0.65
	41	104-T8a	8.38	7.31	8.26	1100	0.34	353.27	702	4.27E-01	1.65
	42	104-T8b	8.54	2.25	6.97	960	85.57	51.04	194	7.05E-03	0.11
	43	207-T8a	7.06	1	4.32	2130	45.61	3.00	1.39	6.71E-03	0.109
	44	207-T8b	7.76	0.678	4.83	1640	0.84	22.15	68.2	1.29E-03	0.116
	45	301-T8a	8.38	1.939	5.25	940	0.14	87.90	254	2.00E-03	0.511
	46	301-T8b	6.76	0.306	5.56	4080	7.20	5.73	20.3	3.96E-03	0.00547
2/9/2007	47	408-T8a	6.67	1.129	4.29	950	55.73	14.98	0.91	2.15E-03	0
	48	408-T8b	6.08	0.166	7.89	2080	8.34	0.14	0.285	6.53E-03	0.0259
	1	105-T1b	7.58	0.905	5.61	530	22.13	1.77	0.0645	5.55E-03	0.286
	2	206-T1b	7.71	0.823	6.55	500	28.20	1.84	0.255	7.82E-03	0.145
	17	103-T5a	7.76	1.587	8.13	300	20.11	64.87	187	6.07E-03	0.234
	19	204-T5a	7.67	0.733	8.87	1020	20.95	5.00	5.94	8.85E-03	0.281
	20	204-T5b	7.03	0.629	3.9	910	12.35	16.31	31.6	3.83E-03	0.00353
	21	308-T5a	6.19	0.514	7.15	320	14.20	8.72	12.5	4.54E-03	0
	23	406-T5a	7.43	0.898	7.52	1080	18.22	15.97	27.4	1.09E-02	0.0155
	24	406-T5b	7.01	0.942	4.74	530	33.51	10.64	15.8	1.11E-02	0.0446
	25	107-T6a	7.15	0.858	4.8	420	6.84	14.73	29.1	4.17E-03	0
	26	107-T6b	7.4	0.558	7.06	320	0.12	3.60	5.92	9.38E-04	0.0083
	27	205-T6a	7.81	1.437	6.6	2000	3.35	72.13	154	5.98E-03	0.138
	28	205-T6b	7.59	0.463	7.43	900	19.34	3.53	3.32	1.68E-03	0.0562
	29	303-T6a	7.43	1.252	3.95	930	2.12	51.18	100	1.14E-03	0.252
	30	303-T6b	6.82	0.613	6.55	310	0.64	20.89	48.3	1.27E-03	0.398
31	401-T6a	7.45	1.243	7.76	530	0.27	42.14	100	9.96E-04	0.0905	
32	401-T6b	6.78	0.342	6.2	1600	3.50	4.89	14	7.55E-03	0	

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>	
2/9/2007	33	106-T7a	8.48	4.78	6.33	650	2.21	133.18	355	6.28E-02	0.656	
	34	106-T7b	7.56	0.885	6.27	1530	21.52	26.22	47.3	2.02E-02	0.00693	
	35	201-T7a	7.6	0.403	6.96	2690	5.24	4.34	14	1.96E-03	0.0574	
	36	201-T7b	7.69	0.306	4.61	930	0.38	3.25	5.52	1.24E-03	0	
	37	306-T7a	4.52	2.21	7.02	790	119.03	43.03	43.7	3.56E-05	0.0101	
	39	405-T7a	7.65	0.718	5.82	1600	10.98	11.88	27.2	1.43E-02	0.0488	
	40	405-T7b	7.41	1.176	6.99	1150	46.71	10.03	10.3	3.29E-01	0.485	
	43	207-T8a	7.52	0.736	8.71	1460	20.45	4.60	4.74	8.02E-03	0	
	44	207-T8b	7.82	0.518	6.39	1000	0.94	13.23	39.7	1.38E-03	0	
	46	301-T8b	6.51	0.331	7.65	1200	11.73	5.55	15.6	2.53E-03	1.12	
	47	408-T8a	6.09	1.053	5.03	640	52.13	9.61	15.8	5.29E-03	0.013	
	48	408-T8b	6.23	0.238	9.8	860	14.92	0.18	1.09	5.85E-03	0.00935	
	3/2/2007	1	105-T1b	7.63	1.051	4.61	300	24.49	6.22	14.8	8.14E-03	0.191
		17	103-T5a	7.68	1.679	4.44	300	33.97	51.19	102	8.79E-03	0.0418
19		204-T5a	7.28	0.778	4.98	790	21.77	12.34	29.1	6.82E-03	0.026	
20		204-T5b	7.11	0.753	2.92	990	22.04	12.34	23.9	7.31E-03	0.0278	
23		406-T5a	6.98	1	5.1	600	23.70	14.47	37.3	8.68E-03	0.0659	
24		406-T5b	6.99	0.887	5.63	260	36.18	5.95	2.22	1.42E-02	0.0959	
25		107-T6a	8.93	0.499	5.46	950	13.16	12.12	40.2	4.28E-03	0.0511	
26		107-T6b	8.11	0.272	5.83	610	0.24	2.31	5.14	1.36E-03	0.0363	
27		205-T6a	7.64	1.159	4.76	450	5.62	55.13	146	2.30E-03	0.0531	
28		205-T6b	7.57	0.503	7.22	1600	21.68	3.24	4.12	7.26E-03	0.0123	
29		303-T6a	8.75	0.989	3.77	900	10.93	41.90	87.1	1.99E-03	0.0984	
30		303-T6b	9.13	0.545	4.33	1200	1.25	15.88	39.9	1.37E-03	0.0378	

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
3/2/2007	31	401-T6a	7.38	1.108	3.56	270	1.48	16.30	82.9	1.08E-03	0.0402
	32	401-T6b	6.66	0.344	4.86	870	4.72	4.52	15.8	8.59E-03	0.0303
	33	106-T7a	8.63	4.57	3.65	1350	0.08	177.67	679	3.88E-02	0.585
	34	106-T7b	7.45	0.954	5.23	2000	28.27	23.73	23.8	2.01E-02	0.0961
	35	201-T7a	7.42	0.414	4.13	1950	7.19	3.70	12.4	7.01E-03	0.0338
	36	201-T7b	7.62	0.3	6.65	1500	0.28	2.74	6.95	9.02E-04	0.0483
	39	405-T7a	7.66	0.798	5.57	750	11.83	7.84	19.3	1.39E-02	0.033
	40	405-T7b	6.98	1.132	3.77	1000	48.80	3.85	10.2	2.97E-01	0.505
	41	104-T8a	8.42	10.54	2.95	410	6.18	326.03	1120	3.83E-01	4.15
	42	104-T8b	8.03	2.24	4.5	350	59.79	46.17	106	5.97E-04	0.133
	43	207-T8a	7.04	0.668	4.06	1020	19.60	2.40	1.72	8.92E-03	0.108
	44	207-T8b	7.56	0.487	6.35	1190	0.26	9.74	27.8	1.85E-03	0.102
	45	301-T8a	8.52	1.756	3.18	350	0.28	77.10	210	2.57E-03	0.351
	46	301-T8b	6.18	0.363	2.5	900	13.10	5.43	12.3	7.49E-03	0.104
	48	408-T8b	5.72	0.238	4.06	380	15.09	0.11	1.11	6.40E-03	0.041
3/23/2007	1	105-T1b	7.68	0.885	5.95	200	58.45	4.08	0.377	4.81E-03	0.285
	5	101-T2b	7.73	0.479	3.06	800	2.45	0.21	0.974	9.01E-03	0.266
	7	302-T2b	7.79	0.646	6.98	340	1.60	0.36	1.21	8.81E-03	0.118
	9	102-T3b	7.63	0.729	5.44	420	28.75	0.24	0.439	1.40E-02	0.249
	11	304-T3b	7.82	0.745	5.24	180	0.51	0.58	1.54	1.81E-02	0.149
	14	202-T4b	7.71	0.576	8.84	275	0.39	0.23	1.07	6.57E-03	0.126
	17	103-T5a	7.53	1.551	2.8	500	126.10	67.32	52	9.54E-03	0.137
	19	204-T5a	7.24	0.729	4.87	550	52.40	0.45	0.405	1.80E-02	0.166
20	204-T5b	6.93	1.141	4.42	1560	122.45	23.35	27.9	8.09E-03	0.0104	

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
3/23/2007	22	308-T5b	7.61	1.186	6.7	240	32.77	77.26	92	8.55E-04	0.13
	23	406-T5a	7.07	0.953	3.56	620	71.11	21.30	22.2	1.36E-02	0.155
	24	406-T5b	6.34	0.884	10.97	580	89.32	1.17	0.55	1.30E-02	0.151
	26	107-T6b	7.13	0.521	4.83	360	3.88	1.36	2.91	8.94E-03	0.0743
	27	205-T6a	7.22	1.343	4.68	2280	19.85	128.91	109	2.14E-02	0.212
	28	205-T6b	7.09	0.541	5.4	1480	31.54	3.20	4.85	1.80E-02	0.031
	29	303-T6a	6.9	1.062	4.75	1080	44.82	59.97	89.6	1.77E-02	0.131
	30	303-T6b	6.87	0.591	4.06	190	2.94	38.46	84.8	1.31E-03	0.0812
	31	401-T6a	7.6	0.915	5.43	270	5.66	72.10	43.4	7.27E-03	0.0818
	32	401-T6b	6.58	0.313	4.97	1140	9.04	6.39	11.5	1.44E-02	0.11
	33	106-T7a	8.37	4.1	2.98	1810	0.20	457.07	535	2.79E-02	0.853
	34	106-T7b	7.3	1.042	4.86	2190	89.80	34.77	26.8	1.77E-02	0.0678
	35	201-T7a	7.28	0.386	4.8	900	9.25	5.64	9.14	4.56E-02	0.0977
	36	201-T7b	7.65	0.32	6.23	350	0.38	2.36	4.8	1.22E-03	0.0053
	37	306-T7a	4.76	1.98	8.69	420	204.90	64.64	37	1.20E-03	0.0868
	39	405-T7a	7.17	0.824	4.34	400	33.97	9.56	19.4	1.77E-02	0.0667
	40	405-T7b	6.96	1.055	5.82	375	123.54	0.93	0.715	3.33E-01	0.617
	41	104-T8a	8.27	7.8	5.8	240	73.14	1084.30	130	4.03E-01	1.75
	44	207-T8b	7.75	0.509	4.82	1280	0.27	19.58	28.3	8.53E-04	0.0467
	45	301-T8a	7.5	1.988	1.98	370	0.22	160.50	17.7	6.22E-04	0.308
46	301-T8b	6.65	0.389	4.27	420	16.41	12.76	22.7	1.01E-03	0.0215	
48	408-T8a	6.68	0.257		170	15.90	0.18	2.13	1.31E-02	0.113	
4/13/2007	1	105-T1b	7.56	0.896	2.72	680	64.20	0.65	0.482	4.08E-03	0.174
	2	206-T1b	7.62	0.88	4.25	680	70.56	0.13	0.403	8.88E-03	0.162
	3	307-T1b	7.89	0.678	4	300	5.22	0.14	1.05	5.46E-03	0.159

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
4/13/2007	4	404-T1b	7.83	0.598	4.23	320	6.01	0.20	0.615	1.32E-02	0.171
	5	101-T2b	7.84	0.95	6.65	1260	102.83	0.33	0.389	3.51E-03	0.123
	6	208-T2b	7.69	0.964	3.94	560	109.59	0.32	0.352	8.11E-03	0.161
	7	302-T2b	7.75	0.56	4.21	670	6.49	0.71	1.54	3.03E-03	0.151
	8	403-T2b	7.68	0.783	5.79	390	11.30	0.18	0.498	1.24E-02	0.261
	9	102-T3b	7.85	0.609	5.4	830	43.07	0.35	0.348	4.07E-03	0.152
	13	108-T4b	8.25	0.893	3.53	325	23.73	0.24	0.432	2.43E-02	0.207
	14	202-T4b	7.76	0.512	3.29	560	0.91	0.45	1.33	1.66E-03	0.14
	15	305-T4b	7.77	1.289	3.8	380	151.13	1.77	0.353	1.79E-02	0.153
	16	402-T4b	7.88	0.675	5.05	490	1.92	0.71	1.76	5.08E-03	0.173
	17	103-T5a	7.06	1.487	3.84	420	174.52	31.44	25.6	7.16E-03	0.112
	19	204-T4a	7.36	0.605	2.62	1190	48.86	0.10	0.333	1.17E-02	0.138
	20	204-T5b	6.89	0.98	2.53	1940	122.29	12.45	0.411	7.18E-03	0.0616
	21	308-T5a	4.83	0.619	3.44	380	62.39	2.28	0.763	1.69E-03	0.0946
	22	308-T5b	7.42	1.233	2.32	700	53.85	81.14	96	3.79E-03	0.143
	23	406-T5a	6.87	0.889	4.61	880	82.36	11.54	8.87	9.61E-03	0.112
	24	406-T5b	6.12	0.752	6.09	390	90.30	0.75	1.59	2.81E-01	0.437
	25	107-T6a	7.64	0.663	3.06	1900	21.66	22.57	25.8	4.86E-03	0.0284
	26	107-T6b	7.12	0.586	3.4	890	34.78	0.25	0.645	3.02E-03	0.0963
	27	205-T6a	7.5	1.595	2.9	960	31.37	161.92	165	6.48E-02	0.784
	28	205-T6b	7.14	0.528	3.01	3150	23.94	2.81	5.12	5.77E-03	0.332
	29	303-T6a	7.56	1.041	3.1	1920	74.45	54.53	51.1	3.60E-03	0
	30	303-T6b	7.75	0.56	4.08	1520	10.27	30.77	35.8	2.28E-03	0.0254
	31	401-T6a	7.56	0.892	4.55	600	24.69	56.00	67.2	5.83E-03	0

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
4/13/2007	32	401-T6b	6.5	0.296	2.12	1400	13.96	3.48	2.28	6.44E-03	0
	33	106-T7a	8.33	3.51	1.01	1680	0.17	494.56	374	1.94E-02	0.549
	34	106-T7b	7.37	0.88	2.83	2290	130.85	15.00	12.4	7.53E-03	0.0865
	37	201-T7a	7.64	0.41	2.18	1940	30.08	7.18	11.9	3.01E-03	0.026
	38	201-T7b	8.05	0.697	1.61	2000	0.02	58.56	77.8	3.26E-03	0.109
	39	405-T7a	7.25	0.809	3.2	420	42.02	7.87	9.65	1.72E-02	0.109
	40	405-T7b	8.93	1.021	4.23	1960	170.39	0.22	0.551	2.22E-01	0.573
	41	104-T8a	8.37	8.93	5.08	400	107.69	1374.22	1080	3.28E-01	0
	42	104-T8b	4.76	1.853	7.7	350	211.40	67.56	43.8	0.00E+00	1.55
	43	207-T8a	6.9	1.069	3.76	1400	114.29	0.61	0.718	5.84E-03	0
	44	207-T8b	7.42	0.715	2.74	1100	1.73	16.91	28	7.16E-04	0.0633
	45	301-T8a	8.49	1.518	2.15	630	7.08	120.32	137	3.45E-03	0.179
	46	301-T8b	6.36	0.403	3.26	1550	22.87	11.46	13.8	7.00E-03	0.058
	47	408-T8a	4.71	0.952	6.4	260	111.36	7.16	2.86	5.59E-02	0.152
	48	408-T8b	6.01	0.245	6.83	350	16.30	0.34	1.68	1.10E-01	0.124
	5/11/2007	1	105-T1b	7.57	0.873	7.15	500	74.12195	0.85	2.452819	0.00000
2		206-T1b	7.5	0.811	10.57	420	62.25732	0.59	2.204051	0.00000	0.103
5		101-T2b	7.43	2.16	6.8	730	344.4613	1.67	3.302664	0.00594	0.141
6		208-T2b	7.39	2.05	9.6	910	298.5988	7.44073	9.11073	0.00000	0.114
7		302-T2b	7.47	1.464	5.87	400	210.7471	0.80	2.16654	0.00000	0.095
8		403-T2b	7.56	1.122	6.58	320	99.93682	0.37	3.131278	0.00000	0.0445
9		102-T3b	7.34	0.718	8.83	990	53.42144	0.18	1.946344	0.00391	0.122
10		203-T3b	7.73	2.45	6.87	330	273.3502	58.295	81.295	0.00000	0.153
17		103-T5a	6.7	1.655	6.46	830	177.7064	8.2485	9.7585	0.00000	0.0948

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
5/11/2007	18	103-T5b	6.89	2.43	7.1	550	276.8215	45.5974	46.7974	0.00000	0.166
	19	204-T5a	7.61	0.562	6	700	63.87862	0.25	1.816268	0.00000	0.0692
	20	204-T5b	7.23	0.867	3.83	1000	151.7585	7.07913	8.24913	0.00000	0.111
	21	308-T5a	4.71	0.67	3.9	550	91.19659	0.61	2.20424	0.00000	0.133
	22	308-T5b	8.14	1.316	3.32	480	60.7272	83.1733	155.8733	0.00533	0.168
	23	406-T5a	6.82	0.854	6.96	910	130.1939	4.16	5.25308	0.00000	0.136
	24	406-T5b	6.01	1.196	8.89	750	118.1289	5.06	6.489799	0.00000	0.137
	25	107-T6a	7.8	0.708	5.36	690	70.97118	21.26086	29.74086	0.00000	0.0849
	26	107-T6b	6.92	1.032	6.31	830	123.0357	1.48	2.618553	0.00000	0.0667
	27	205-T6a	7.7	1.582	6.37	2800	56.81188	154.1967	208	0.06216	0.291
	28	205-T6b	7	0.53	7.04	2250	20.06	2.62	3.977488	0.00000	0.0955
	29	303-T6a	4.68	3.13	5.22	2500	353.3581	139.2156	158	0.00000	0.135
	30	303-T6b	6.54	1.284	6.18	520	151.3143	48.75141	51.44141	0.00000	0.149
	31	401-T6a	7.99	0.868	6.26	620	63.82375	40.608	47.9	0.00000	0.0958
	32	401-T6b	6.38	0.292	3.12	1130	14.45	2.25	4.259027	0.00000	0.0998
	33	106-T7a	8.16	3.9	3.64	1020	0.63	387.3609	524	0.08076	0.864
	34	106-T7b	6.94	0.551	6.21	2000	117.4202	2.38	4.209341	0.00000	0.0912
	35	201-T7a	6.9	0.697	3.62	3500	107.1456	2.87	4.602051	0.00000	0.0773
	36	201-T7b	7.99	1.356	4.28	4200	0.36	124.1722	208	0.00000	0.148
	37	306-T7a	4.14	2.21	4.71	710	218.751	41.3328	67.3328	0.00000	0.118
	39	405-T7a	7.26	0.897	3.3	1760	104.1975	3.80	5.778216	0.00000	0.107
	40	405-T7b	7.03	1.796	8.59	570	213.4957	0.24	1.75387	0.33847	0.442
	41	104-T8a	7.91	7.18	2.89	1000	226.065	709.1424	783	0.12011	0.986
	42	104-T8b	4.56	1.851	4.4	600	194.6615	49.0282	81.9282	0.00000	0.108



**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
5/11/2007	43	207-T8a	6.73	2.49	9.42	2600	305.3879	27.94077	36.22077	0.00000	0.0809
	44	207-T8b	7.54	0.86	9.45	2400	10.15	28.25727	54.65727	0.00000	0.0802
	45	301-T8a	7.14	1.558	2.7	720	27.67452	90.6502	91.6	0.00000	0.189
	46	301-T8b	6.29	0.407	7.02	1900	27.55071	9.53089	17.32089	0.00000	0.0691
	47	408-T8a	4.6	0.882	10.65	680	131.575	2.25	3.19301	0.00000	0.0962
	48	408-T8b	6.09	0.5	13.46	1010	65.7218	0.29	0.726727	0.00000	0.0743
6/8/2007	1	105-T1b	7.21	0.947	7.3	900	81.015	0.20	0.727724	0.00000	0.0346
	2	206-T1b	7.07	0.741	7.92	860	77.01359	0.27	0.792386	0.00000	0.0312
	3	307-T1b	7.54	0.756	9.06	400	7.73	0.55	1.104615	0.00000	0.0319
	4	404-T1b	6.74	0.573	10.23	310	8.16	0.18	0.718138	0.02196	0.0332
	5	101-T2b	7.54	1.957	6.99	1200	193.8564	0.29	0.823144	0.00000	0.0307
	6	208-T2b	6.85	1.746	6.45	1800	225.6398	0.06	0.583431	0.00000	0.0331
	7	302-T2b	7.52	1.367	8.99	660	125.5101	0.68	1.214529	0.00000	0.0337
	8	403-T2b	6.79	1.129	9.52	520	90.9111	0.95	1.480132	0.00359	0.029
	9	102-T3b	7.64	0.703	8.43	1400	33.98443	0.87	1.412689	0.00119	0.0328
	10	203-T3b	6.21	3	6.18	1250	349.197	77.077	86.607	0.00000	0.0324
	12	407-T3b	7.31	1.024	10.87	300	65.93569	0.77	1.335556	0.00986	0.0334
	13	108-T4b	7.59	1.009	8.48	350	30.14063	1.00	1.601623	0.03720	0.0376
	14	202-T4b	7.49	0.571	7.47	1100	37.53329	0.25	0.787839	0.00000	0.0327
	15	305-T4b	7.62	5.31	5.86	340	612.9305	345.5382	375.2382	0.01858	0.0353
17	103-T5a	6.86	1.653	4.5	1100	196.3916	1.15	1.680837	0.00000	0.0323	
18	103-T5b	5.37	2.06	5.17	1000	239.7515	11.23103	11.87003	0.00000	0.0341	
19	204-T5a	6.83	0.637	5.89	1800	52.95895	0.61	1.128911	0.00000	0.032	
20	204-T5b	6.71	0.802	6.3	9540	123.844	3.77	4.347298	0.00000	0.0334	

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
6/8/2007	22	308-T5b	6.65	1.494	4.83	1020	140.2499	74.3369	83.3269	0.00000	0.0345
	23	406-T5a	6.86	0.877	8.03	3380	119.7274	1.40	1.928114	0.00000	0.0329
	24	406-T5b	5.9	0.928	8.76	1940	105.9789	0.42	0.944596	0.00000	0.0327
	25	107-T6a	7.67	0.869	6.48	1300	101.9033	13.75175	14.36775	0.00199	0.0305
	26	107-T6b	7.22	0.846	6.96	3600	65.65714	0.72	1.255434	0.00000	0.0305
	27	205-T6a	7.57	1.401	7.82	2000	38.60603	135.7879	152.1879	0.01889	0.039
	28	205-T6b	7.45	0.575	7.49	3900	37.91176	1.73	2.261276	0.00000	0.0306
	29	303-T6a	7.93	1.971	6.19	1360	203.5526	80.954	83.014	0.00000	0.0325
	30	303-T6b	5.92	1.109	6.06	380	139.9349	24.38391	24.99491	0.00000	0.0313
	31	401-T6a	7.16	0.902	7.53	1260	93.92161	31.6529	32.5609	0.00000	0.0316
	32	401-T6b	6.36	0.3	6.99	3580	18.85	0.69	1.227018	0.00020	0.0305
	33	106-T7a	8.59	3.39	1.04	3200	0.71	337.3741	362.8741	0.06007	0.0876
	34	106-T7b	7.24	0.772	7.18	2900	79.22637	1.88	2.44649	0.02559	0.039
	35	201-T7a	6.76	0.668	4.14	3000	92.90591	2.37	2.956116	0.00000	0.0303
	36	201-T7b	7.58	0.866	2.48	3200	2.04	87.6669	101.0669	0.00000	0.0342
	37	306-T7a	4.04	1.969	9.38	520	198.8245	37.8793	38.3983	0.00000	0.0334
	38	306-T7b	4.72	1.442	8.04	3150	146.6838	0.55	1.067079	0.00000	0.0324
	39	405-T7a	7.4	0.991	8.28	680	108.4159	1.03	1.544882	0.00000	0.0325
	40	405-T7b	7.21	1.596	9.66	510	193.2833	0.21	0.726031	0.41272	0.0705
	41	104-T8a	7.53	4.76	2.54	870	441.4608	511.355	532.955	0.01394	0.0679
	42	104-T8b	4.4	1.757	5.7	780	195.0105	29.08136	29.79336	0.00000	0.0336
	43	207-T8a	6.51	2.54	6.87	3100	231.4567	34.99824	35.52724	0.00000	0.0312
	44	207-T8b	7.76	0.642	6.16	3400	3.67	16.50125	18.00125	0.00000	0.0317
	45	301-T8a	7.32	1.228	4.56	1050	63.45552	34.63133	35.25433	0.00000	0.0345
	46	301-T8b	6.27	0.341	7.4	3950	25.95941	5.61	6.251526	0.00961	0.0337

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
6/8/2007	47	408-T8a	6.01	0.415	8.17	670	37.81905	0.21	0.744681	0.00000	0.0295
	48	408-T8b	4.55	0.857	11.53	1420	94.06097	0.38	0.913275	0.00000	0.0318
7/10/2007	2	206-T1b	7.26	0.838	7.34	330	50.83259	0.262254	0.588	0.014098	0.0381
	3	307-T1b	7.26	0.661	6.53	450	5.830788	0.309294	0.599	0.014433	0.0382
	4	404-T1b	7.18	0.606	7.01	290	8.549245	0.444159	0.598	0.019511	0.0386
	5	101-T2b	7.06	1.434	7.08	690	167.7486	0.693272	1.286272	6.10E-03	0.0398
	6	208-T2b	7.32	1.44	8.26	570	158.3119	0.383005	0.599	0.013108	0.0373
	7	302-T2b	7.32	1.096	8.4	420	176.4381	0.43108	0.599	5.77E-03	0.0384
	8	403-T2b	7.05	1.202	5.57	430	109.1263	0.473441	0.591	0.011616	0.0376
	9	102-T3b	7.23	0.528	7.69	740	30.92793	0.570606	0.591	4.84E-03	0.0378
	10	203-T3b	7.37	2.17	6.5	550	355.9679	70.0679	73.7779	7.60E-03	0.0354
	11	304-T3b	7.32	0.788	7.98	210	2.454172	0.798728	1.402728	0.022113	0.0514
	12	402-T3b	7.22	1.012	6.66	250	40.11957	0.551781	0.606	0.015605	0.0389
	13	108-T4b	7.15	0.975	6.08	470	24.18062	2.734377	3.341377	0.041882	0.0395
	14	202-T4b	7.35	0.529	6.86	500	46.4288	0.62562	1.22762	0.015453	0.0367
	15	305-T4b	7.55	3.83	7.22	520	431.1883	0.576076	16.1	4.83E-03	0.0376
	16	402-T4b	7.38	1.192	6	390	15.48978	1.76443	2.41943	0.019858	0.039
	17	103-T5a	6.97	1.517	6.15	510	12.9084	1.12394	1.71294	0.013809	0.0376
	18	103-T5b	4.86	2.37	7.89	260	207.4249	0.394621	0.598	0.013069	0.0414
	19	204-T5a	6.68	0.532	5.06	850	59.74999	1.255555	1.855555	8.60E-03	0.0365
	20	204-T5b	6.59	0.46	3.23	1150	55.47843	0.751544	1.355544	6.66E-03	0.0348
	21	308-T5a	6.26	1.045	5.74	580	170.9957	2.269697	3.529697	0.010419	0.0367
	22	308-T5b	6.6	1.507	3.75	1150	122.7901	51.0899	55.5399	3.07E-03	0.0379
	23	406-T5a	6.41	2.06	6.34	790	149.3033	44.3987	47.3687	4.85E-03	0.0412
	24	406-T5b	5.09	1.764	5.02	310	126.9402	29.27122	30.09922	0.013394	0.0367

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
7/10/2007	25	107-T6a	6.79	0.828	3.7	1670	72.64132	5.49639	6.14139	2.65E-03	0.0357
	26	107-T6b	6.78	0.79	4.7	1600	70.62221	4.337792	4.937792	9.52E-03	0.0363
	27	205-T6a	7.52	1.29	5.05	1200	35.1486	0.696005	16.2	0.0206	0.0399
	28	205-T6b	6.88	0.617	3.98	1200	56.10386	2.60775	3.21375	0.020208	0.0355
	29	303-T6a	5.19	2.04	5.77	590	182.0644	1.456964	9.65	9.04E-03	0.0358
	30	303-T6b	5.86	1.089	4.84	1040	100.7561	25.78328	26.63428	5.77E-03	0.0366
	31	401-T6a	6.41	1.005	5.54	860	126.809	20.01277	20.97377	8.85E-03	0.0319
	32	401-T6b	6.02	0.341	2.44	1050	23.82416	2.1734	2.7824	4.85E-03	0.0352
	33	106-T7a	7.65	2.68	3.8	810	23.96518	1.342822	24.2	7.43E-03	0.084
	34	106-T7b	6.86	0.609	4.39	1350	0.729583	1.72538	2.31638	0.025273	0.0364
	35	201-T7a	6.96	0.774	3.93	1000	87.91633	1.067442	1.675442	0.016499	0.0356
	36	201-T7b	7.86	1.162	1.3	1200	48.33228	2.484976	16.3	5.64E-03	0.0403
	37	306-T7a	3.96	2.35	5.7	760	273.9117	42.602	44.192	7.74E-03	0.0371
	38	306-T7b	4.72	1.285	6.4	300	144.3431	0.98729	1.58329	0.011	0.0365
	39	405-T7a	6.9	1.889	4.72	800	182.3818	0.47668	0.606	4.92E-03	0.0371
	40	405-T7b	6.79	1.736	5.44	1100	207.0186	4.298861	4.892861	0.016784	0.0761
	41	104-T8a	7.23	4.08	6.8	460	477.7038	0.564315	17.6	0.389722	0.0509
	42	104-T8b	4.35	1.706	6.72	360	199.8903	18.8054	19.3924	6.81E-03	0.0386
	43	207-T8a	6.7	2.21	5.28	1500	277.9408	26.607	27.425	0.018877	0.0355
	44	207-T8b	7.24	0.905	3.8	1150	64.05824	20.52163	23.89163	0.010995	0.039
	45	301-T8a	7.91	1.155	5.92	500	0.839378	26.45102	27.33002	5.69E-03	0.0377
	46	301-T8b	6.37	0.418	4.59	1200	36.41085	3.99103	4.62003	7.13E-03	0.0352
	47	408-T8a	4.49	0.821	6.13	410	102.1203	0.99754	1.58354	8.24E-03	0.0353
	48	408-T8b	5.94	0.64	5.08	860	65.36461	0.678705	1.264705	5.29E-03	0.0354
8/9/2007	7	302-T2b	7.3	1.191	5.71	460	124.6986	0.740466	1.327466	9.62E-03	0.0395

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
8/9/2007	9	102-T3b	7.23	0.628	6.36	560	23.70714	0.62985	1.23385	0.013272	0.0372
	15	305-T4b	7.73	3.41	5.52	310	24.69736	0.575635	15.6	0.01584	0.0382
	19	204-T5a	7.6	0.569	3.51	950	32.66303	41.99641	42.59141	0.021512	0.0384
	20	204-T5b	7	0.571	5.27	450	41.9777	0.459225	0.585	0.018074	0.0364
	22	308-T5b	6.61	1.526	3.67	920	35.00971	0.424414	2.83	0.012399	0.0373
	23	406-T5a	4.64	1.99	5.3	300	239.5689	35.89092	36.86092	6.70E-03	0.0404
	24	406-T5b	4.55	1.678	4.78	440	197.5236	1.54934	2.13634	6.99E-03	0.0374
	25	107-T6a	7.17	0.811		570	51.73841	1.338648	1.926648	9.04E-03	0.0356
	26	107-T6b	7.19	0.797		880	36.50792	2.830502	3.417502	9.89E-03	0.0357
	27	205-T6a	7.63	1.395	4.19	1100	15.41873	0.424098	17.6	0.010452	0.0393
	28	205-T6b	7.07	0.618	3.17	1040	17.43188	42.28247	42.89947	0.022849	0.0361
	29	303-T6a	4.75	2.1	5.33	400	289.3624	81.68661	88.36661	0.010074	0.0367
	30	303-T6b	5.96	1.324	4.66	680	208.6469	22.37252	23.23052	6.01E-03	0.0351
	33	106-T7a	7.86	3.05	2.25	530	56.38598	14.74228	33	7.58E-03	0.0945
	34	106-T7b	7.15	0.783	3.33	950	0.973723	49.3324	49.9194	0.020224	0.0376
	35	201-T7a	7	0.701	2.95	780	73.03981	0.935956	1.522956	0.018496	0.0355
	36	201-T7b	7.45	1.368	1.08	780	42.25471	2.353611	16	0.012314	0.0393
	39	405-T7a	7.34	1.746	4.05	485	0.48638	39.98663	40.56963	6.30E-03	0.0388
	40	405-T7b	7.36	1.49	5.55	730	199.339	4.06497	4.65097	0.01494	0.0687
	43	207-T8a	6.96	2.03	4.5	780	252.7327	0.375344	0.591	0.348871	0.036
	44	207-T8b	7.29	0.997	2.44	1050	63.82855	0.947001	2.85	0.010346	0.0389
	46	301-T8b	6.35	0.387	5.24	380	0.972715	25.48407	26.11107	4.47E-03	0.0348
	47	408-T8a	4.86	0.784	5.97	240	84.7799	2.392288	2.979288	9.00E-03	0.0362
	48	408-T8b	6.11	0.586	5.85	360	58.29957	0.675803	1.261803	5.22E-03	0.0359

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
9/7/2007	3	307-T1b	7.26	0.726	4.21	360	7.01	0.456053	0.598	0.011139	0.0381
	21	308-T5a	6.42	1.368	4.3	470	0.374386	0.50626	0.639	0.013815	0.0366
	22	308-T5b	6.24	1.628	3.22	1110	185.265	39.76282	40.34982	5.79E-03	0.0365
	23	406-T5a	4.3	2.16	3.87	340	196.8185	17.17679	17.83279	6.29E-03	0.0394
	25	107-T6a	6.73	0.758		300	55.60697	0.84865	1.44365	0.013865	0.0353
	26	107-T6b	7.14	0.792		610	30.96792	0.551966	0.596	9.98E-03	0.0361
	27	205-T6a	7.46	1.448	3.04	1000	16.43404	0.475865	17.9	0.015097	0.0401
	28	205-T6b	7.19	0.594	3.64	750	15.63272	42.30378	43.16878	0.026118	0.0364
	29	303-T6a	4.67	2.13	4.11	300	20.94131	1.489483	4.04	0.012217	0.0356
	30	303-T6b	4.78	1.375	4.14	650	186.5929	4.1472	4.7342	5.33E-03	0.0355
	31	401-T6a	5.82	1.014	4.06	400	114.0204	3.33779	3.92479	3.06E-03	0.0363
	32	401-T6b	6.24	0.442	4.34	280	34.87906	1.306387	1.901387	3.22E-03	0.0357
	33	106-T7a	7.92	2.98	2.12	580	32.06974	0.408743	27.1	9.79E-03	0.0897
	34	106-T7b	7.19	0.743	3.72	700	3.423533	48.71616	49.31816	0.017126	0.036
	35	201-T7a	7	0.944	3.96	420	96.93645	0.943293	1.530293	9.22E-03	0.0352
	36	201-T7b	7.34	1.179	1.13	850	2.6295	2.696742	12.6	0.011824	0.0388
	37	306-T7a	4.02	2.11	4.53	310	2.143794	38.35056	39.53056	5.01E-03	0.0371
	38	306-T7b	4.97	1.142	5.15	180	125.2716	0.72998	1.31698	0.010114	0.0366
	39	405-T7a	7.35	1.785	3.72	520	223.0567	0.549683	0.585	3.10E-03	0.0391
	40	405-T7b	7.44	1.275	4.16	380	156.8198	0.343248	0.586	0.021423	0.0652
	41	104-T8a	4.9	3.96	4	570	472.4284	0.304036	16.7	0.329832	0.0413
	43	207-T8a	6.78	1.97	4.64	330	245.1982	1.2644	1.8514	2.67E-03	0.0349
	44	207-T8b	7.27	0.97	2.71	780	62.62239	1.236086	1.54	6.97E-03	0.0386
	45	301-T8a	6.82	1.221	3.59	400	2.841621	5.10713	5.70613	4.46E-03	0.0367
	46	301-T8b	6	0.4	3.54	790	35.12007	5.084409	5.691409	2.88E-03	0.0348

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
10/12/2007	13	108-T4b	7.71	0.828	5.39	240	24.42737	0.744646	1.377646	7.07E-03	0.0404
	17	103-T5a	6.51	1.65	4.8	300	205.4984	5.506543	6.138543	0.012535	0.0377
	23	406-T5a	3.91	2.01	5.06	190	231.5418	1.187948	1.832948	0.013829	0.0413
	25	107-T6a	7.46	0.708	5.64	370	44.78913	0.417444	1.051444	0.015272	0.0377
	26	107-T6b	7.45	0.692		450	28.5377	0.254609	0.890609	8.73E-03	0.0372
	27	205-T6a	7.69	1.886	2.13	1380	28.11125	0.713734	17.01373	0.012868	0.0415
	28	205-T6b	7.24	0.593	2.1	1800	10.96077	45.38074	46.01674	0.028761	0.0367
	30	303-T6b	4.83	1.3	5.32	300	15.43542	1.587568	2.219568	0.01108	0.0368
	31	401-T6a	4.63	1.05	4.59	360	124.0851	0.440608	0.631	3.10E-03	0.0389
	32	401-T6b	6.42	0.421	4.58	290	34.09469	0.185012	0.639	5.28E-03	0.0369
	33	106-T7a	7.25	3.95	4.21	600	548.9529	0.532267	0.632	0.011788	0.04
	34	106-T7b	7.52	0.694	5.33	350	48.4996	0.39819	0.636	0.014254	0.0382
	35	201-T7a	6.98	0.954	3.63	590	107.8559	0.43018	0.631	0.019358	0.0379
	36	201-T7b	7.18	1.02	2.5	960	76.26574	0.229481	1.97	0.010562	0.0386
	39	405-T7a	7.59	1.832	4.11	450	45.31199	24.64099	25.27299	8.93E-03	0.038
	40	405-T7b	7.87	1.193	4.88	410	152.5589	0.29605	0.632	0.011856	0.0637
	41	104-T8a	4.47	5.15	4.49	420	614.7035	0.265773	19.2	0.290094	0.0416
	43	207-T8a	7.02	1.877	5.64	290	237.5366	1.05688	1.68688	8.94E-03	0.0414
	44	207-T8b	7.26	0.953	3.08	760	279.2643	0.766118	1.414118	0.021789	0.0387
	45	301-T8a	7.13	1.093	5.76	250	101.437	0.666052	1.299052	9.82E-03	0.0408
	46	301-T8b	6.82	0.471	6.63	250	39.76803	0.454985	1.098985	0.016289	0.0347
47	408-T8a	4.66	0.773	5.84	260	87.24434	1.837971	2.471971	5.37E-03	0.038	
1/23/2008	1	105-T1b	7.56	0.38	7.01	430	24.87	0.23	3.9	0.03	0.1124
	3	307-T1b	6.44	0.34	6.51	340	0.87	0.35	0.842	0.02	0.02906

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
1/23/2008	4	404-T1b	6.34	0.24	6.89	290	0.17	0.57	0.722	0.03	0.02906
	5	101-T2b	7.21	0.22	7.24	900	0.87	1.06	1.595	0.04	0.02906
	6	208-T2b	6.9	0.25	7.31	180	112.18	0.52	0.688	0.02	0.02906
	7	302-T2b	6.34	0.28	6.2	950	15.93	0.3	0.579	0.02	0.02906
	10	203-T3b	6.89	0.67	6.88	450	289.4929	0.4	0.45	0.02	0.02906
	11	304-T3b	6.46	0.44	7.25	380	81	0.29	0.39	0.02	0.02906
	12	407-T3b	5.73	0.17	8.16	180	437.5882	0.35	0.38	0.03	0.02906
	13	108-T4b	7.3	0.25	6.7	530	18.03	0.4	0.708	0.05	0.02906
	14	202-T4b	6.9	0.14	6.58	250	7.24	0.71	1.98	0.01	0.02906
	15	305-T4b	6.42	1.23	6.7	390	493.6288	0.41	0.4722	0.02	0.0938
	16	402-T4b	6.34	0.26	6.64	420	16.36	0.36	1.13	0.02	0.02906
	20	204-T5b	5.98	1.55	6.36	580	648.673	0.55	0.996	0.02	0.02906
	21	308-T5a	6.12	0.34	6.73	1100	90.17	0.18	0.746	0.01	0.02906
	22	308-T5b	5.54	1.14	4.2	1600	422.2501	3.84	6.09	0.01	0.372
	25	107-T6a	6.97	0.26	5.29	530	49.57	0.46	3.4	0.02	0.33
	26	107-T6b	6.7	0.26	5.58	960	30.5	0.72	0.761	0.03	0.197
	27	205-T6a	6.75	0.98	3.14	3200	302.2865	355.6297	363.4297	0.03	0.318
	28	205-T6b	6.58	0.53	3.75	2750	170.78	65.17	68.3	0.01	0.18
	29	303-T6a	4	0.69	6.84	300	256.4933	35.0409	37.0209	0.01	0.276
	30	303-T6b	4.71	0.4	5.77	420	145.13	0.48	0.48	0	0.02906
	31	401-T6a	4.81	0.32	5.6	400	122.1	0.4	0.688	0.01	0
	32	401-T6b	5.48	0.14	6.56	180	40.24	0.35	1.85	0.01	0
	33	106-T7a	6.93	1.6	5.83	400	635.4709	0.58	1.078	0.02	0.02906
	34	106-T7b	6.33	1.02	5.13	1900	401.415	0.33	0.77	0.01	0



**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>	
1/23/2008	35	201-T7a	5.83	1.05	3.74	2200	514.6956	33	33.176	0.01	0	
	36	201-T7b	5.73	1.33	4.35	1300	600.6697	129.3816	213.2816	0.01	0	
	37	306-T7a	3.61	0.64	5.44	350	238.9327	25.3	37.3	0.02	0	
	39	405-T7a	6.46	0.33	5.8	430	320.954	0.28	0.521	0.02	0	
	40	405-T7b	5.86	0.16	5.84	210	153.18	0.2	0.332	0.27	0.2656	
	41	104-T8a	4.29	0.00202	5.74	450	814.6682	495.0124	524.0124	0.01	0.02906	
	43	207-T8a	6.5	0.62	5.55	420	291.4191	1.47	1.801	0.02	0	
	44	207-T8b	6.3	1.23	4.44	2200	728.3003	87.8054	87.9724	0.01	0	
	45	301-T8a	5.69	0.41	6.08	230	105.27	1.12	1.475	0	0	
	46	301-T8b	4.52	1.1	5.4	1200	456.1368	19.64	19.904	0.01	0	
	47	408-T8a	4.45	0.03	7.78	190	107.15	0.94	1.226	0.01	0.02906	
	3/24/2008	1	105-T1b	6.9	0.43	5.13	420	35.54	0.198373	0.776	0.010567	0.1386
		2	206-T1b	7.06	0.26	5.26	5010	2.047724	0.155027	1.38	0.00E+00	0.02906
		3	307-T1b	6.37	0.32	6.36	330	2.826361	0.077606	0.746	1.90E-03	0.02906
4		404-T1b	6.81	0.23	6.07	320	0.773276	0.079747	1.61	7.64E-03	0.02906	
5		101-T2b	7.21	0.22	5.64	720	1.121714	0.124959	0.737	3.73E-03	0.02906	
6		208-T2b	6.69	0.28	5.38	520	58.27	0.108591	1.21	0.00E+00	0.02906	
8		403-T2b	6.38	0.66	5.98	350	164.71	0.131254	0.194454	0.011505	0.02906	
9		102-T3b	7.38	0.15	5.91	370	0.433844	0.070895	0.444895	5.42E-03	0.02906	
10		203-T3b	6.33	0.61	4.69	310	158.93	0.163062	0.283062	1.67E-04	0.1033	
11		304-T3b	6.34	0.44	5.41	530	89.45	0.239096	0.239096	3.78E-03	0.0819	
12		407-T3b	6.07	0.43	5.88	310	373.79	0.07746	0.17	3.81E-03	0.02906	
13		108-T4b	6.8	0.29	5.79	400	16.29968	0.1194	1.57	7.36E-03	0.0712	
14		202-T4b	6.67	0.16	5.68	380	11.96911	1.150587	2.13	9.32E-05	0.02906	

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
3/24/2008	15	305-T4b	6.16	1.15	5.57	400	444.16	1.156871	1.306871	1.00E-03	0.02906
	16	402-T4b	4.27	0.34	6.38	250	21.00111	0.152032	1.13	7.62E-03	0.02906
	17	103-T5a	6.96	0.73	5.9	350	427.13	0.070695	0.070695	1.61E-05	0.02906
	19	204-T5a	5.95	1.98	3.4	1430	694.8	3.163193	3.509193	0.016408	0.3346
	20	204-T5b	5.93	1.46	4.04	1425	615.53	0.109615	1.12	6.06E-03	0.0593
	21	308-T5a	5.34	1.1	6.15	680	564.28	0.136529	1.58	5.21E-03	0.1306
	22	308-T5b	5.22	1.25	3.64	1550	568.38	0.753139	1.3	2.79E-03	0.02906
	23	406-T5a	4.2	1.54	4.08	1360	659.9	58.09448	97.4	0.01145	0.2746
	25	107-T6a	6.59	0.44	5.33	1250	201.49	0.267498	0.271678	1.58E-05	0.02906
	26	107-T6b	6.58	0.87	5.22	1900	509.63	0.076332	0.383	8.61E-04	0.02906
	27	205-T6a	6.44	0.91	3.25	2580	182.2	60.17	92.1	7.86E-03	0.0691
	28	205-T6b	6.51	0.61	2.75	2090	337.38	9.19	28.5	7.48E-03	0.02906
	30	303-T6b	4.87	0.64	4.49	2000	401.7527	5.461061	6.901061	0.00E+00	0
	31	401-T6a	4.59	0.79	2.93	1030	386.5646	34.9	54	1.91E-03	0.0613
	32	401-T6b	4.66	0.64	3.16	850	734.9383	97.04	110.04	8.40E-04	0.02906
	33	106-T7a	6.38	2.44	3.1	1100	527.5043	39.4883	39.6743	7.63E-03	0.02906
	34	106-T7b	6.27	1.02	5.36	1800	634.5445	0.144694	0.657	4.56E-03	0.02906
	35	201-T7a	5.64	1.4	3.02	1275	608.8904	45.9206	75.7206	3.20E-03	0.02906
	36	201-T7b	5.75	1.26	2.8	1350	688.0764	50.48045	50.77845	2.54E-03	0.02906
	37	306-T7a	3.93	1.77	5.36	850	461.0632	57.95431	59.06431	5.76E-03	0.02906
	39	405-T7a	6.33	0.8	5	360	631.3654	2.100172	2.100172	6.95E-04	0.02906
	40	405-T7b	6.02	1.14	3.2	1150	671.8008	11.46923	11.47697	0.210685	0.2616
	41	104-T8a	4.47	2.47	5.25	380	295.6334	70.8391	71.1921	5.32E-03	0.0047
	42	104-T8b	4.13	0.7	6.63	220	363.6831	1.73299	2.15299	0.0177	0.0403
44	207-T8b	6.3	2.17	2.78	2020	120.3077	24.8883	25.5	3.14E-04	0.03484	

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
3/24/2008	45	301-T8a	5.71	0.42	5.7	400	624.7817	0.197549	0.197549	4.21E-03	0.02906
	46	301-T8b	4.5	1.21	4.01	2850	540.26	25.37977	25.84577	2.32E-03	0.02906
	48	408-T8b	4.64	0.1	4.92	1400	85.19221	0.553651	0.553651	1.60E-03	0.0075
5/2/2008	1	105-T1b	7.05	0.46	3.98	800	66.31	1.02244	1.73	3.24E-04	0.02906
	2	206-T1b	6.73	0.36	3.85	2100	1.411747	0.527307	0.733	0.010083	0.02906
	3	307-T1b	6.68	0.39	4.63	500	2.870615	0.143975	0.55	0.016761	0
	4	404-T1b	6.72	0.3	4.72	380	1.105857	0.060431	0.234	0.017544	0.0942
	5	101-T2b	7.2	0.33	5.7	5130	76.29	0.927694	1.32	3.14E-03	0.0492
	6	208-T2b	6.36	0.38	6.1	5200	223.28	0.301018	0.301018	5.24E-03	0.03684
	7	302-T2b	6.49	0.36	3.79	760	13.2521	0.1066	0.802	3.21E-03	0.02906
	8	403-T2b	6.33	0.81	4.11	990	13.31303	0.127066	0.614	1.03E-03	0.1101
	9	102-T3b	7.3	0.22	4.75	1000	272.84	0.728958	0.760558	3.29E-03	0.02906
	10	203-T3b	6.67	0.73	4.87	2670	151.05	0.191657	0.909	5.56E-03	0
	11	304-T3b	6.64	0.6	4.75	670	481.58	0.059954	0.060618	7.08E-04	0.02906
	12	407-T3b	6.07	1.1	5.2	1600	470.21	0.134269	0.134269	5.30E-03	0.02906
	13	108-T4b	6.84	0.31	4.87	590	18.6667	0.116766	1.25	0.032279	0.1406
	14	202-T4b	6.72	0.21	4.94	650	6.365238	0.185705	1.04	3.65E-04	0.02906
	15	305-T4b	5.94	1.2	5.76	710	36.29	0.594339	0.594339	2.41E-03	0.0969
	16	402-T4b	6.3	0.35	4.62	345	463.52	0.143833	1.6	7.78E-03	0.02906
	17	103-T5a	5.81	1.24	4.61	9180	549.88	38.04743	56.04743	4.94E-03	0.0024
	18	103-T5b	5.26	1.47	5.76	6680	580.02	23.54719	29.96719	2.35E-03	0.1138
	19	204-T5a	6.25	2.19	4.43	3980	498.63	0.217329	1.1	0.015821	0.2306
	20	204-T5b	5.68	1.48	2.98	5410	473.28	0.078035	0.078035	9.75E-03	0.02906
	21	308-T5a	5.77	1.19	4.44	3300	558.26	0.082942	0.183	3.21E-03	0.1083
	22	308-T5b	4.9	1.59	3.11	690	527.78	0.771772	0.771772	3.02E-03	0.0732

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
5/2/2008	23	406-T5a	3.92	1.44	5.3	9900	674.99	50.0465	91.2465	0.01273	0.1516
	24	406-T5b	4.2	2.28	4.34	780	220.47	49.27843	52.96843	9.92E-03	0.02906
	25	107-T6a	6.58	0.58	4.24	610	407.73	0.243941	0.762	7.21E-04	0.02906
	26	107-T6b	6.66	0.99	4.53	675	308.4	0.104539	0.104539	5.54E-03	0.02906
	27	205-T6a	6.32	1.03	2.9	1400	107.45	61.22989	205	0.019747	0.1596
	28	205-T6b	6.43	0.58	2.47	2660	360.93	36.11396	55.91396	0.011499	0.02906
	29	303-T6a	4.02	1.74	5.41	9720	313.52	49.45784	71.7	6.75E-04	0.02906
	30	303-T6b	4.45	0.68	2.79	8800	426.9	1.96656	1.96656	8.09E-04	0.02906
	31	401-T6a	3.64	0.9	2.96	1630	326.16	30.61567	45.41567	3.83E-03	0.02906
	32	401-T6b	4.75	0.73	3.34	850	662.3638	15.95435	15.95435	7.65E-03	0.1022
	33	106-T7a	6.32	3.01	2.84	3500	425.5558	38.16985	56.36985	0.00E+00	0.02906
	34	106-T7b	6.19	1.07	4.04	10220	530.6439	0.231796	0.231796	7.45E-03	0.02906
	35	201-T7a	5.52	1.67	2.53	1390	522.8067	42.93832	50.73832	5.63E-03	0.0802
	36	201-T7b	5.6	1.45	2.28	1380	715.2429	45.76597	66.26597	2.25E-03	0.02906
	37	306-T7a	3.61	2.87	4.02	2850	707.6136	59.61912	94.41912	6.49E-03	0.02906
	38	306-T7b	4.14	3.1	3.6	6530	672.3658	48.07505	70.57505	5.15E-03	0.02906
	39	405-T7a	5.94	2.29	4.08	3030	503.3781	48.1441	49.5441	0.017078	0.02906
	40	405-T7b	5.78	1.33	2.7	1680	724.3829	3.846006	3.846006	0.236763	0.3716
	41	104-T8a	4.93	4.23	4.29	4760	607.836	75.80244	181	4.33E-03	0.3396
	42	104-T8b	3.94	2.52	4.74	3920	641.0947	24.94584	25.14584	4.45E-03	0.02906
	43	207-T8a	5.69	2.24	2.1	1900	733.3188	59.14285	67.3	4.19E-03	0.02906
	44	207-T8b	6.2	2.37	1.87	1800	582.3743	46.55909	46.55909	4.45E-03	0.02906
	45	301-T8a	5.8	1.52	4.88	1350	213.1196	0.262268	0.262268	1.70E-03	0.0029
	46	301-T8b	4.35	1.05	2.44	10220	709.0429	5.882124	5.882124	0.00E+00	0.0207
	47	408-T8a	4.17	1.7	4.25	6350	454.6283	33.08691	33.08691	3.58E-03	0.02906

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
5/2/2008	48	408-T8b	4.81	0.35	4.55	10350	134.8372	0.156312	0.156312	2.72E-03	0.6936
6/5/2008	20	204-T5b	5.45	0.92	3.63	740	96.39183	42.0497	57.7497	0.010979	0.124
	22	308-T5b	4.93	1.79	4.73	290	46.96909	3.245037	3.280037	5.00E-03	0.161
	23	406-T5a	4.17	1.1	5.95	330	304.1761	2.700504	2.735504	0.242156	0.26
	25	107-T6a	6.3	0.75	4.89	350	614.4828	27.51299	27.68299	0.014689	0.143
	27	205-T6a	6.43	0.95	3.22	890	346.7318	52.1537	88.7537	0.020511	0.146
	28	205-T6b	6.32	0.43	3.49	640	257.4661	38.4227	38.4577	5.00E-03	0.135
	29	303-T6a	4.66	0.86	4.7	520	125.1587	12.83644	18.91644	5.00E-03	0.138
	30	303-T6b	4.45	0.38	3.37	1000	757.5436	130.555	196.655	0.010479	0.142
	31	401-T6a	4.43	0.95	4.41	325	243.9527	48.43556	48.47056	5.00E-03	0.19
	32	401-T6b	4.49	0.75	5.63	400	242.078	30.49974	30.53474	5.00E-03	0.17
	33	106-T7a	6.11	2.54	4.53	500	384.768	64.98622	65.24322	0.012709	0.146
	34	106-T7b	6.23	1.38	3.43	1000	173.4784	19.46433	19.49933	0.021777	0.196
	35	201-T7a	5.94	1.62	4.2	350	121.8624	2.73507	2.77007	0.016336	0.142
	36	201-T7b	5.28	1.2	3.47	680	152.7352	154.7504	173	0.018096	0.169
	37	306-T7a	3.74	2.48	5.19	510	519.6946	0.34502	0.38002	0.010512	0.143
	39	405-T7a	6.71	2.08	5.3	300	209.8242	13.77091	13.80591	5.00E-03	0.163
	40	405-T7b	6.38	1.21	6.92	500	1049.671	69.81255	69.84755	0.018646	0.166
	42	104-T8b	4.17	1.58	5.11	290	94.1744	0.675214	0.710214	0.011279	0.146
	43	207-T8a	7.3	1.52	3.24	1180	443.3646	71.6504	73.2404	0.01057	0.146
	44	207-T8b	6.16	1.87	3.14	970	524.7664	61.46502	71.30502	5.00E-03	0.132
	45	301-T8a	6	1.9	5.52	415	329.2041	1.294171	1.384971	5.00E-03	0.155
	46	301-T8b	5.05	0.28	3.56	930	124.2344	79.6517	124.8517	5.00E-03	0.143
	47	408-T8a	4.67	0.53	4.39	550	117.0915	9.31713	9.35213	5.00E-03	0.146

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
7/11/2008	13	108-T4b	7.64	0.82	3.58	720	328.3523	5.291964	6.591964	0.022623	0.142
	16	402-T4b	7.28	0.9	4.67	350	105.4055	3.132588	3.167588	5.00E-03	0.151
	22	308-T5b	6.91	4.85	4.61	300	67.44345	3.040396	3.075396	5.00E-03	0.14
	27	205-T6a	6.51	1.9	2.28	2100	252.7437	42.85888	42.96388	5.00E-03	0.137
	29	303-T6a	3.88	1.78	2.8	720	126.8172	0.584107	0.619107	5.00E-03	0.143
	30	303-T6b	4.4	0.72	2.9	1000	213.9443	127.07	127.105	5.00E-03	0.147
	31	401-T6a	3.74	2.2	3.7	420	43.10137	0.119449	0.154449	0.018282	0.157
	32	401-T6b	3.98	1.9	3.8	800	330.07	36.02193	36.05693	0.011109	0.158
	33	106-T7a	7	4.64	2.39	1100	213.3948	5.396732	5.431732	0.023901	0.188
	34	106-T7b	6.54	2.88	2.86	1300	297.6128	264.435	640.435	0.041761	0.235
	35	201-T7a	6.05	3.6	2.75	780	183.2836	100.8746	109	0.020518	0.173
	36	201-T7b	5.81	2.3	2.41	1250	421.1462	58.36026	58.39526	0.012545	0.153
	37	306-T7a	3.74	4.98	3.68	380	153.2079	0.186743	0.221743	0.012673	0.146
	38	405-T7a	7.09	3.8	2.49	850	160.844	50.95412	51.29312	0.028051	0.154
	40	405-T7b	6.24	2.9	3.33	700	194.8728	0.170523	0.205523	0.239717	0.264
	41	104-T8a	7.09	7.39	1.58	800	38.83316	0.117126	0.223	0.031447	0.188
	42	104-T8b	3.75	3.07	5.08	370	350.3855	59.44672	60.26072	0.012458	0.149
	43	207-T8a	6.03	2.9	3.6	1050	328.0118	29.74076	29.77576	0.010736	0.145
	44	207-T8b	6.74	4.3	3.08	1100	357.2566	30.41119	30.44619	0.010933	0.156
	45	301-T8a	6.46	3.62	3.65	650	334.2132	0.249004	0.284004	0.019111	0.206
46	301-T8b	4.94	0.52	3.49	450	185.8145	75.81932	81.24932	0.013263	0.164	
47	408-T8a	3.9	0.5	2.95	500	189.322	0.324246	0.359246	0.026774	0.167	
9/18/2008	12	407-T3b	6.78	1.81	3.4	260	129.468	0.165271	0.200271	0.010504	0.148
	13	108-T4b	7	1.45	4.33	180	105.1902	1.170816	1.205816	5.00E-03	0.156
	15	305-T4b	6.28	7.01	3.8	200	322.37	35.8878	35.9228	5.00E-03	0.164
	17	103-T5a	5	1.176	1.78	1100	948.8392	35.142	35.177	0.027773	0.65

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
9/18/2008	20	204-T5b	6.02	10.64	1.89	900	573.2581	23.5537	23.5911	0.021945	0.332
	21	308-T5a	6.24	6.66	2.08	1800	367.1404	12.15659	12.19159	0.012312	0.237
	22	308-T5b	6.83	3.87	2.57	750	75.9506	1.754608	2.565608	0.010605	0.163
	23	406-T5a	3.82	5.2	1.87	1200	355.0167	44.28224	44.35254	0.026509	0.195
	24	406-T5b	4.53	7.83	2.6	300	700.175	53.61761	53.65261	0.020966	0.213
	27	205-T6a	7.13	1.35	2.42	1000	172.309	92.1152	147.4152	0.013037	0.155
	28	205-T6b	6.96	0.65	3.7	180	61.15241	18.72602	23.02602	0.020908	0.142
	29	303-T6a	4	1.6	2.92	400	96.4437	22.7983	39.2983	0.011896	0.15
	30	303-T6b	7.19	2.41	1.27	2500	104.3314	51.89123	51.92623	0.023635	0.186
	31	401-T6a	4.33	2.26	3.08	500	115.662	55.31353	58.42353	5.00E-03	0.153
	33	106-T7a	7	3.4	2.9	400	303.3335	1.715877	1.750877	0.018068	0.153
	36	201-T7b	6.56	1.84	2.63	550	402.6265	39.86813	43.79813	5.00E-03	0.135
	40	405-T7b	6.38	2.78	2.92	1400	186.9139	0.188297	0.223297	0.22458	0.286
	41	104-T8a	6.8	5.48	2.85	350	1181.337	105.8413	317	0.03221	0.242
	43	207-T8a	4.81	2.03	3.3	350	474.3034	0.30011	0.33511	5.00E-03	0.135
	44	207-T8b	6.74	3.48	2.06	950	188.9861	4.730546	4.765546	5.00E-03	0.137
	46	301-T8b	4.71	4.61	1.54	2200	194.6753	29.927	29.962	5.00E-03	0.145
	10/23/2008	17	103-T5a	6.15	8.83	4.74	350	608.8717	44.81275	44.84775	0.034045
20		204-T5b	4.6	9.71	4.89	320	604.8033	54.17898	54.21398	0.04175	0.288
21		308-T5a	6.05	6.85	5.25	280	496.1222	0.247696	0.282696	0.023793	0.244
23		406-T5a	3.59	5.13	6.07	500	437.6619	15.02477	15.05977	0.036371	0.204
27		205-T6a	5.73	1.35	4.65	670	137.1022	62.27735	96.67735	5.00E-03	0.159
33		106-T7a	6.71	2.83	5.96	270	355.9622	0.370286	0.405286	0.021335	0.161
36		201-T7b	5.84	1.71	4.45	480	197.3072	10.7575	10.7925	0.012348	0.251

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
10/23/2008	40	405-T7b	5.87	3.59	8.7	390	345.9147	0.247449	0.282449	0.123342	0.259
	41	104-T8a	6.64	4.77	4.23	330	416.989	316.3678	456.3678	0.032562	0.209
	43	207-T8a	5.02	1.97	7.9	210	250.93	0.37364	0.40864	0.018425	0.135
	44	207-T8b	6.46	3.43	4.72	500	388.94	1.456922	1.491922	0.011837	0.137
	46	301-T8b	4.8	4.03	4.44	375	372.1848	45.46831	45.50331	5.00E-03	0.228
12/4/2008	4	404-T1b	6.35	0.65	8.43	300	1.410721	0.361406	1.13	3.50E-03	0.0942
	5	101-T2b	7.31	1.12	9.04	350	190.0239	0.106014	0.548	0.012684	0.111
	10	203-T3b	6	1.9	10.51	150	404.3912	0.395541	0.548	6.63E-03	0.142
	13	108-T4b	7.23	0.51	8.03	470	6.500294	0.244273	1.45	0.012684	0.116
	15	305-T4b	6.79	3.26	8.24	420	618.4974	0.208464	0.221	1.29E-03	0.115
	17	103-T5a	6.42	7.21	4.61	500	424.9444	1.563707	1.939	2.73E-03	0.206
	18	103-T5b	4.05	7.96	7.61	300	1144.324	107.1067	120.559	0.024109	0.294
	20	204-T5b	4	9.62	7.4	530	1227.425	44.72535	45.0768	0.026224	0.272
	22	308-T5b	6.82	3.4	10.42	150	338.8271	0.332941	0.449	0.036122	0.184
	23	406-T5a	3.52	3.72	6.6	300	622.7648	15.38669	16.225	0.038469	0.213
	27	205-T6a	4.89	1.07	6.71	440	192.8664	53.92033	58.2	0.012684	0.149
	31	401-T6a	4.41	5.03	6.1	440	661.6088	163.8346	176.6	0.010487	0.262
	32	401-T6b	6.25	0.65	8.03	360	16.05499	0.912729	1.57	1.70E-03	0.12
	33	106-T7a	7	1.1	9.3	200	360.6567	0.420102	0.548	0.012684	0.127
	36	201-T7b	4.76	0.89	7.97	300	277.3972	1.070972	1.537	0.012684	0.113
	40	405-T7b	5.58	2.03	9.35	500	343.1251	0.279549	0.355	0.078623	0.214
	41	104-T8a	4.85	3.46	6.54	320	576.3406	315.7396	354.9	4.91E-03	0.155
	43	207-T8a	5.31	1.46	8.41	210	245.7699	0.404705	1.42	0.012684	0.125
	44	207-T8b	6.01	2.38	8.16	300	417.6472	0.272363	0.703	2.74E-03	0.104
	46	301-T8b	4.17	2.73	5.89	380	391.4411	38.6085	40.0796	3.36E-03	0.114



**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
12/28/2008	1	105-T1b	7.89	1.780	6.2	240	1.576529	0.167438	3.53	0.01661	0.154
	2	206-T1b	7.71	1.280	5.18	560	0.524509	0.140157	1.75	0.024329	0.139
	3	307-T1b	7.50	2.070	6.47	220	3.37583	0.080829	0.64	0.024901	0.141
	6	208-T2b	7.90	1.320	6.2	430	2.070113	0.294071	3.76	0.077738	0.177
	7	302-T2b	7.95	1.420	8.36	150	94.79009	0.256292	1.64	0.034743	0.186
	8	403-T2b	7.37	2.420	7.25	380	176.8042	0.288705	0.548	0.022126	0.143
	11	304-T3b	7.67	2.450	6.22	150	142.4152	0.281555	0.548	0.055884	0.162
	12	407-T3b	6.16	6.070	7.47	260	148.4991	0.442558	0.548	0.023886	0.16
	13	108-T4b	7.32	0.711	5.95	250	13.30821	0.122843	0.584	0.023886	0.118
	14	202-T4b	7.93	0.708	6.3	360	38.43899	0.409402	0.548	0.013048	0.122
	15	305-T4b	7.29	3.640	7.54	190	471.2564	0.330409	0.944	0.342944	0.349
	17	103-T5a	6.41	9.070	4.67	230	1032.766	0.555439	1.16	0.087187	0.624
	18	103-T5b	4.04	12.190	5.67	580	1355.135	118.8061	119.069	0.038961	0.386
	19	204-T5a	5.91	12.410	6.03	960	1882.434	1.372804	1.5	0.014995	0.688
	20	204-T5b	4.11	9.250	7.1	800	1113.084	29.36727	30.522	0.037398	0.295
	21	308-T5a	6.52	6.420	4.45	920	813.3162	0.177446	1.17	0.012684	0.158
	23	406-T5a	3.24	3.950	5.61	1050	593.0298	19.18297	19.45	0.026591	0.208
	24	406-T5b	4.22	6.070	7.17	1300	1038.042	4.091363	5.93	0.012684	0.283
	25	107-T6a	4.72	8.150	3.52	1400	902.0558	89.9102	97.13	0.015162	0.293
	27	205-T6a	4.33	1.570	5.32	700	191.8391	39.8509	40.7	6.95E-03	0.175
	28	205-T6b	6.28	6.140	4.56	950	691.2182	31.82812	32.38	0.020266	0.273
	30	303-T6b	6.00	3.700	2.97	3250	339.9632	1.03215	1.05	1.63E-03	0.169
	31	401-T6a	4.43	6.220	3.82	1600	521.4322	131.3919	145.56	0.012883	0.289
	32	401-T6b	4.82	6.110	5.39	1320	717.9297	28.39175	28.84	3.27E-03	0.203

**Appendix B. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	DO, mg l <sup>-1</sup>	V, ml	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
12/28/2008	34	106-T7b	6.25	6.670	3.65	2000	941.0055	1.369361	1.556	0.007633	0.184
	36	201-T7b	4.50	3.880	6.21	930	496.2679	29.35547	38.06	1.56E-04	0.135
	37	306-T7a	4.43	8.540	4.81	1450	916.9386	47.38741	68.68	6.77E-03	0.185
	38	306-T7b	5.07	3.430	3.93	1000	304.8453	0.362006	3.45	6.43E-04	0.144
	39	405-T7a	6.60	9.200	4.02	800	1324.189	59.76082	60.762	0.059754	0.193
	40	405-T7b	6.80	3.450	6.7	1500	473.3671	0.176363	0.609	0.215844	0.222
	43	207-T8a	5.00	2.130	6.09	710	260.8445	1.448554	1.57	1.76E-03	2.29
	44	207-T8b	6.61	5.320	4.6	15000	713.5035	0.203087	0.659	0.014106	0.132
	46	301-T8b	4.05	4.340	5.21	1330	449.0236	29.32349	30.0548	5.40E-03	0.114
	47	408-T8a	5.01	4.110	5.08	1200	704.2946	85.4532	120.2	0.010716	0.245
	48	408-T8b	3.48	3.370	7.66	1100	412.0337	60.01404	60.0548	3.02E-03	0.132

**Appendix C. Individual pH, EC, N and P forms in leachate collected from suction lysimeters over the study period (July 2006-December 2008).**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
9/8/2006	50	204-T5	6.38	0.513	4.355949	1.243526	1.859429	0.034577	0.117291
	51	308-T5	6.82	0.395	25.72537	1.084567	25.9225	0.036044	0.117291
	52	406-T5	6.78	0.809	26.40009	32.28019	71.71304	0.007383	0.117291
	54	205-T6	7.25	0.713	18.23969	34.63379	80.62273	0.039169	0.117291
	57	106-T7	7.2	0.483	7.47511	21.50268	36.57066	0.032488	0.117291
	58	201-T7	8.68	1.175	28.78771	43.98194	111.3653	0.029926	0.117291
	59	306-T7	6.66	1.49	5.51723	15.56639	23.72299	0.024422	0.281116
	60	405-T7	6.07	0.5	0.021589	0	1.820292	0.007383	0.117291
	62	207-T8	7.28	0.715	50.96051	20.36194	2.699836	0.048429	0.117291
	64	408-T8	6.37	2.09	25.44185	17.34418	174.853	0.007383	0.117291
10/6/2006	54	205-T6	7.4	0.83	33.13487	26.50415	47.57113	0.043431	0.117291
	57	106-T7	5.46	0.287	13.0075	1.487999	2.014453	0.041523	0.117291
	58	201-T7	7.93	0.386	9.539323	0.52423	1.734101	0.041056	0.117291
	60	405-T7	6.8	0.749	28.50015	9.601124	12.74113	0.040455	0.132599
	62	207-T8	7.23	1.128	46.26099	6.934545	6.970819	0.026445	0.117291
11/3/2006	49	308-T5	4.92	0.332	37.14878	2.009536	2.1	0.001868	0.1032
	52	406-T5	6.93	0.398	9.718308	0.686655	0.773854	0.008483	0.079238
	53	103-T6	7.97	1.091	30.97596	100.1335	157.9198	0.013038	0.056619
	54	205-T6	7.56	0.905	62.94453	27.41308	28.53358	0.003708	0.099959
	58	201-T7	7.86	0.248	1.500087	0.227295	0.90706	0.003335	0.07657
	62	207-T8	8.24	0.961	115.7809	9.48311	10.432	0	0.097598
	63	301-T8	6.21	0.453	23.72486	3.815867	4.044613	0.001058	0.094961
	64	408-T8	4.8	0.284	21.75652	2.107035	2.249012	0	0.064953
12/1/2006	49	103-T5	8.38	1.543	17.06907	156.977	268.7243	0.013446	0.140092
	50	204-T5	7.64	0.328	10.57348	10.53668	13.7138	0.001252	0.069216

## Appendix C. Continued.

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
12/1/2006	51	308-T5	7.28	0.192	11.09441	4.153244	5.590796	0	0.062273
	52	406-T5	6.78	0.25	2.632655	0.722997	0.740741	0.004614	0.087117
	53	107-T6	8.99	1.68	4.005443	189.5882	361.0986	0.008691	0.10982
	54	205-T6	7.45	0.435	8.434793	1.356754	2.026046	0	0.080826
	55	303-T6	7.27	0.097	0.326503	0.672035	1.420532	0	0.0563
	56	401-T6	8.64	1.051	12.59567	127.5512	223.2146	0.013641	0.05922
	57	106-T7	6.06	0.178	6.847796	0.6948	0.724743	0	0.059308
	58	201-T7	8.33	0.169	0.458783	0.177893	0.756722	0	0.097008
	59	306-T7	5.07	0.431	29.83109	9.475513	11.1345	0	0.100529
	60	405-T7	6.12	0.455	35.57954	12.23491	12.84427	0.002003	0.094062
	61	104-T8	8.69	0.216	3.542853	2.540834	4.229287	0.024625	0.049083
	62	207-T8	8.4	0.53	39.33931	0.257803	0.440974	0.002342	0.085567
	63	301-T8	6.17	0.243	3.361155	11.72861	13.8411	0.001289	0.051081
	64	408-T8	7.54	0.178	5.542503	0.15868	0.645918	0.002298	0.49249
12/15/2006	50	204-T5	8.5	0.637	17.28825	39.39106	48.0464	0.001485	0.002678
	52	406-T5	6.96	0.76	18.90825	36.74804	64.6578	0	0.002678
	53	107-T6	8.9	1.297	58.43862	137.1418	244.2044	0.009959	0.02623
	54	205-T6	7.33	0.744	63.76084	11.68316	12.82209	0	0.02623
	56	401-T6	8.76	0.912	45.98418	94.60514	143.1839	0.001899	0.002678
	58	201-T7	8.73	0.206	1.211998	2.005813	2.843925	0.001292	0.002678
	60	405-T7	6.61	0.281	10.43847	2.059923	2.273122	0.001206	0.01515
	62	207-T8	7.86	0.291	4.504017	1.045557	1.120084	0	0.002678
	63	301-T8	8.1	0.309	15.56825	7.60308	8.779639	0.003534	0.002678
	64	408-T8	7.06	0.173	4.600831	2.723246	3.424267	0.0062	0.002678
1/5/2007	49	103-T5	5.51	0.358	27.49788	3.045895	3.419945	0	0.002678

## Appendix C. Continued.

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
1/5/2007	50	204-T5	8.08	0.456	9.287571	26.95924	41.42194	0.00201	0.002678
	52	406-T5	4.91	0.431	36.15388	1.164245	1.178609	0	0.01477
	53	107-T6	7.77	0.723	31.27326	53.5997	88.16566	0.001659	0.48818
	54	205-T6	8.17	0.59	56.90902	4.636141	5.171437	0	0.002678
	55	303-T6	6.62	0.325	25.78036	2.127399	2.875081	0	0.002678
	56	401-T6	4.38	0.292	27.35774	7.91934	8.763853	0	0.002678
	57	106-T7	6.16	0.396	26.47747	1.330222	2.092366	0	0.01477
	58	201-T7	8.77	0.287	2.430419	0.282547	0.328211	0.00113	0.024352
	59	306-T7	4.56	0.377	29.0448	1.092775	1.552678	0	0.01906
	60	405-T7	6.48	0.219	5.964233	4.077781	5.27811	0.002459	0.002678
	62	207-T8	8.16	0.322	4.60458	17.20694	17.47119	0.002831	0.002678
	63	301-T8	5.63	0.27	16.44205	0.317718	0.372883	0	0.002678
	64	408-T8	6.33	0.382	34.26328	0	0	0	0.439551
	1/19/2007	49	103-T5	4.78	0.351	16.58	3.83	5.97	1.76E-03
52		406-T5	6.47	0.288	11.07	0.08	1.08	2.21E-03	0.04
53		107-T6	8.23	1.218	19.76	35.03	79.4	5.32E-03	0.07
54		205-T6	7.08	0.602	22.07	0.13	1.39	4.43E-03	0.0633
57		106-T7	6.28	0.264	11.29	0.17	1.49	2.11E-03	0.0588
58		201-T7	8.04	0.218	1.73	0.03	2.89	2.06E-03	0.0247
59		306-T7	5.26	0.384	13.77	1.04	5.08	1.26E-03	0.0193
60		405-T7	6.16	0.221	5.48	1.32	3.76	2.63E-03	0.0433
61		104-T8	8.96	0.22	7.54	0.14	2.08	7.93E-03	0.0309
62		207-T8	8.14	0.37	18.10	0.16	1.38	2.37E-03	0.0441
63	301-T8	5	0.473	15.39	10.40	23.8	7.32E-04	0.047	
64	408-T8	6.06	1.065	59.00	0.34	1.2	1.28E-03	0.0219	

## Appendix C. Continued.

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
2/9/2007	54	205-T6	6.75	0.438	10.98	0.49	2.12	4.79E-03	0.0212
	57	106-T7	5.8	0.365	11.18	0.94	1.12	2.82E-03	0.06
	58	201-T7	7.76	0.347	5.52	0.04	1.26	2.99E-03	0.0587
	60	405-T7	6.34	0.281	16.17	0.06	1.31	3.43E-03	0.0387
	62	207-T8	7.21	0.536	15.78	0.71	1.94	5.80E-03	0.0355
3/2/2007	50	204-T5	6.21	0.298	20.66	1.97	2.27	2.59E-03	0.0388
	54	205-T6	6.62	0.407	10.55	0.38	1.34	5.91E-03	0.0295
	57	106-T7	5.72	0.408	14.49	5.24	5.18	5.11E-03	0.0418
	58	201-T7	8.75	0.26	12.58	0.10	1.7	3.82E-03	0.0291
	60	405-T7	7.48	0.296	19.75	0.03	1.34	6.32E-03	0.0704
3/23/2007	62	207-T8	8.41	0.481	18.63	0.18	1.54	4.23E-03	0.029
	54	205-T6	7.08	0.519	41.48	0.48	1.87	1.90E-03	0.0374
	58	201-T7	7.63	0.282	12.26	0.23	1.82	3.86E-03	0.0323
4/13/2007	62	207-T8	7.28	0.564	45.72	0.17	1.02	2.39E-03	0.0428
	50	204-T5	8.18	0.251	6.65	0.23	1.42	6.60E-03	0.0417
	54	205-T6	6.52	0.402	26.56	0.80	1	1.00E-02	0.073
	57	106-T7	4.55	0.386	24.96	5.56	7.38	7.17E-04	0
	58	201-T7	7.39	0.281	10.08	0.31	1.19	2.51E-03	0
6/8/2007	60	405-T7	7.1	0.697	66.86	0.48	0.392	8.95E-03	0
	50	204-T5	7.2	0.451	40.78646	0.32	0.85993	0.00000	0.029
	53	107-T6	7.25	0.324	2.48	0.18	0.738507	0.00000	0.0312
	54	205-T6	6.6	0.742	68.36721	13.19	14.17459	0.00000	0.0299
	57	106-T7	4.53	0.388	29.11125	4.14	4.758079	0.00000	0.0294
	58	201-T7	7.12	0.454	25.2932	5.23	5.87578	0.00000	0.0296
	60	405-T7	6.52	0.856	79.57629	0.15	0.683929	0.00000	0.0298
	62	207-T8	7.2	1.183	125.5447	0.36	0.89301	0.00000	0.0308
64	408-T8	5.92	0.454	37.28078	0.08	0.609708	0.00000	0.03	

## Appendix C. Continued.

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
10/12/2007	57	106-T7	5.46	1.104	120.9859	0.640016	1.274016	5.21E-03	0.038
5/2/2008	49	103-T5	6.18	0.44	33.29721	4.864947	4.9	0.028126	0.02906
	50	204-T5	6.48	0.16	37.98846	0.088555	0.093	2.15E-03	0.002
	51	308-T5	5.79	0.1	12.82642	0.092151	0.12	0.00E+00	0
	52	406-T5	6.15	0.21	247.02	0.246921	0.26	4.91E-03	0.0054
	53	107-T6	6.4	0.65	75.97	22.47316	23.67316	0.042626	0.0574
	54	205-T6	6.53	0.13	12.68662	5.071438	7.71	4.90E-03	0.0026
	55	303-T6	5.64	0.4	53.51205	31.93653	48.1	0.00E+00	0.02906
	56	401-T6	6.39	0.18	36.21407	0.671549	29.2	0.011628	0.0582
	57	106-T7	6.2	0.13	15.97465	3.439399	5.129399	4.88E-03	0.02906
	58	201-T7	6.49	0.14	6.745479	0.473054	0.776	7.26E-03	0.02906
	59	306-T7	6.3	0.21	31.85464	0.117879	0.23	9.57E-04	0
	60	405-T7	6	0.29	42.65344	0.759442	0.8	0.011215	0.02906
	61	104-T8	7.1	0.11	0.503823	0.079583	0.177083	0.048764	0.02906
	62	207-T8	6.21	0.24	37.82501	0.208795	15.3	6.58E-03	0.02906
	63	301-T8	7.25	0.08	17.78231	0.174483	0.233583	0.011801	0.02906
	64	408-T8	6.34	0.17	17.99858	0.064897	0.064897	0.01096	0.02906
6/5/2008	54	205-T6	6.89	0.31	62.34386	0.086817	0.121817	0.010862	0.141
7/11/2008	54	205-T6	6.62	0.57	36.09	0.171223	0.206223	0.015628	0.156
	57	106-T7	5.55	0.74	143.5274	0.017533	0.035	0.01242	0.142
	58	306-T7	6.48	0.35	12.13609	0.134605	0.169605	0.034707	0.152
	60	405-T7	5.94	2.08	125.5623	0.139427	0.174427	0.10992	0.156
10/23/2008	58	106-T7	6.13	2.17	251.2396	0.198774	0.233774	0.010806	0.28
12/4/2008	54	205-T6	5.95	0.19	17.42526	0.170571	0.548	9.24E-04	0.125
	57	106-T7	5.59	0.88	126.5575	0.266647	0.548	5.66E-04	0.11

**Appendix C. Continued.**

Sampling date	ID	Treatment	pH	EC, mS cm <sup>-1</sup>	NO <sub>3</sub> -N, mg l <sup>-1</sup>	NH <sub>4</sub> -N, mg l <sup>-1</sup>	TKN, mg l <sup>-1</sup>	PO <sub>4</sub> -P, mg l <sup>-1</sup>	TKP, mg l <sup>-1</sup>
12/28/2008	51	308-T5	5.61	0.365	19.16085	0.25713	0.571	0.012684	0.0998
	52	406-T5	6.36	0.961	63.84993	0.111495	1.62	1.21E-03	0.103
	54	205-T6	4.85	2.440	228.5182	13.8676	15.0548	4.55E-03	0.125
	55	303-T6	5.38	0.591	69.04913	0.796401	1.83	0.012684	0.0984
	56	401-T6	5.68	0.624	74.87501	0.216765	0.548	0.012684	0.0981
	57	106-T7	6.10	0.415	25.73874	0.159091	0.548	0.012684	0.104
	59	306-T7	6.62	0.338	17.28944	0.101913	0.569	6.76E-04	0.106
	62	207-T8	5.80	0.239	14.92538	0.104653	0.548	0.012684	0.1
	63	301-T8	8.00	0.556	4.006082	0.220238	1.2	0.02785	0.0942



**Appendix D. Oxidation-reduction potential in the biosolids seams throughout the study  
(August 2006-December 2008).**

Sampling date	ID	Treatment	Eh, mV
10-Aug-06	1	301-T8	
10-Aug-06	2	301-T8	29
10-Aug-06	3	301-T8	-529
10-Aug-06	4	301-T8	49
10-Aug-06	5	301-T8	
10-Aug-06	6	301-T8	-92
10-Aug-06	7	301-T8	-126
10-Aug-06	8	107-T6	-22
10-Aug-06	9	107-T6	54
10-Aug-06	10	107-T6	
10-Aug-06	11	107-T6	-42
10-Aug-06	12	107-T6	66
10-Aug-06	13	107-T6	-122
10-Aug-06	14	105-T1	481
10-Aug-06	15	105-T1	593
10-Aug-06	16	105-T1	
10-Aug-06	17	105-T1	548
10-Aug-06	18	105-T1	593
10-Aug-06	19	105-T1	602
8-Sep-06	1	301-T8	-62
8-Sep-06	2	301-T8	12
8-Sep-06	3	301-T8	-122
8-Sep-06	4	301-T8	-6
8-Sep-06	5	301-T8	-383
8-Sep-06	6	301-T8	-95
8-Sep-06	7	301-T8	-52
8-Sep-06	8	107-T6	-188
8-Sep-06	9	107-T6	-20
8-Sep-06	10	107-T6	-145
8-Sep-06	11	107-T6	11
8-Sep-06	12	107-T6	-17
8-Sep-06	13	107-T6	-3
8-Sep-06	14	105-T1	490
8-Sep-06	15	105-T1	573
8-Sep-06	16	105-T1	
8-Sep-06	17	105-T1	481
8-Sep-06	18	105-T1	493

**Appendix D. Continued.**

Sampling date	ID	Treatment	Eh, mV
8-Sep-06	19	105-T1	569
6-Oct-06	1	301-T8	-70
6-Oct-06	2	301-T8	7
6-Oct-06	3	301-T8	-129
6-Oct-06	4	301-T8	-23
6-Oct-06	5	301-T8	-220
6-Oct-06	6	301-T8	-78
6-Oct-06	7	301-T8	-58
6-Oct-06	8	107-T6	-123
6-Oct-06	9	107-T6	-70
6-Oct-06	10	107-T6	-173
6-Oct-06	11	107-T6	-91
6-Oct-06	12	107-T6	4
6-Oct-06	13	107-T6	3
6-Oct-06	14	105-T1	460
6-Oct-06	15	105-T1	575
6-Oct-06	16	105-T1	
6-Oct-06	17	105-T1	511
6-Oct-06	18	105-T1	537
6-Oct-06	19	105-T1	607
3-Nov-06	1	301-T8	-62
3-Nov-06	2	301-T8	26
3-Nov-06	3	301-T8	-118
3-Nov-06	4	301-T8	-13
3-Nov-06	5	301-T8	-195
3-Nov-06	6	301-T8	-76
3-Nov-06	7	301-T8	-63
3-Nov-06	8	107-T6	-111
3-Nov-06	9	107-T6	-68
3-Nov-06	10	107-T6	-162
3-Nov-06	11	107-T6	-76
3-Nov-06	12	107-T6	15
3-Nov-06	13	107-T6	-6
3-Nov-06	14	105-T1	487
3-Nov-06	15	105-T1	603
3-Nov-06	16	105-T1	
3-Nov-06	17	105-T1	523

**Appendix D. Continued.**

Sampling date	ID	Treatment	Eh, mV
3-Nov-06	18	105-T1	524
3-Nov-06	19	105-T1	578
1-Dec-06	1	301-T8	-50
1-Dec-06	2	301-T8	40
1-Dec-06	3	301-T8	-142
1-Dec-06	4	301-T8	-6
1-Dec-06	5	301-T8	-183
1-Dec-06	6	301-T8	-82
1-Dec-06	7	301-T8	-62
1-Dec-06	8	107-T6	-98
1-Dec-06	9	107-T6	-40
1-Dec-06	10	107-T6	-148
1-Dec-06	11	107-T6	-69
1-Dec-06	12	107-T6	-16
1-Dec-06	13	107-T6	27
1-Dec-06	14	105-T1	470
1-Dec-06	15	105-T1	553
1-Dec-06	16	105-T1	208
1-Dec-06	17	105-T1	461
1-Dec-06	18	105-T1	459
1-Dec-06	19	105-T1	589
19-Jan-07	1	301-T8	7
19-Jan-07	2	301-T8	7
19-Jan-07	3	301-T8	-50
19-Jan-07	4	301-T8	-39
19-Jan-07	5	301-T8	-203
19-Jan-07	6	301-T8	-128
19-Jan-07	7	301-T8	-106
19-Jan-07	8	107-T6	-76
19-Jan-07	9	107-T6	-141
19-Jan-07	10	107-T6	-162
19-Jan-07	11	107-T6	-126
19-Jan-07	12	107-T6	-49
19-Jan-07	13	107-T6	33
19-Jan-07	14	105-T1	480
19-Jan-07	15	105-T1	592
19-Jan-07	16	105-T1	238

**Appendix D. Continued.**

Sampling date	ID	Treatment	Eh, mV
19-Jan-07	17	105-T1	453
19-Jan-07	18	105-T1	499
19-Jan-07	19	105-T1	637
2-Mar-07	1	301-T8	-28
2-Mar-07	2	301-T8	32
2-Mar-07	3	301-T8	-18
2-Mar-07	4	301-T8	-46
2-Mar-07	5	301-T8	-239
2-Mar-07	6	301-T8	-152
2-Mar-07	7	301-T8	-112
2-Mar-07	8	107-T6	-129
2-Mar-07	9	107-T6	-90
2-Mar-07	10	107-T6	-208
2-Mar-07	11	107-T6	-169
2-Mar-07	12	107-T6	-66
2-Mar-07	13	107-T6	-23
2-Mar-07	14	105-T1	471
2-Mar-07	15	105-T1	551
2-Mar-07	16	105-T1	258
2-Mar-07	17	105-T1	473
2-Mar-07	18	105-T1	468
2-Mar-07	19	105-T1	609
13-Apr-07	1	301-T8	55
13-Apr-07	2	301-T8	15
13-Apr-07	3	301-T8	38
13-Apr-07	4	301-T8	-63
13-Apr-07	5	301-T8	-162
13-Apr-07	6	301-T8	-149
13-Apr-07	7	301-T8	-71
13-Apr-07	8	107-T6	-198
13-Apr-07	9	107-T6	-174
13-Apr-07	10	107-T6	-222
13-Apr-07	11	107-T6	-207
13-Apr-07	12	107-T6	-93
13-Apr-07	13	107-T6	-11
13-Apr-07	14	105-T1	462
13-Apr-07	15	105-T1	592

**Appendix D. Continued.**

Sampling date	ID	Treatment	Eh, mV
13-Apr-07	16	105-T1	292
13-Apr-07	17	105-T1	452
13-Apr-07	18	105-T1	459
13-Apr-07	19	105-T1	583
11-May-07	1	301-T8	72
11-May-07	2	301-T8	17
11-May-07	3	301-T8	92
11-May-07	4	301-T8	-74
11-May-07	5	301-T8	-235
11-May-07	6	301-T8	-190
11-May-07	7	301-T8	-93
11-May-07	8	107-T6	-277
11-May-07	9	107-T6	-275
11-May-07	10	107-T6	-269
11-May-07	11	107-T6	-221
11-May-07	12	107-T6	-76
11-May-07	13	107-T6	15
11-May-07	14	105-T1	495
11-May-07	15	105-T1	575
11-May-07	16	105-T1	325
11-May-07	17	105-T1	449
11-May-07	18	105-T1	491
11-May-07	19	105-T1	485
8-Jun-07	1	301-T8	110
8-Jun-07	2	301-T8	40
8-Jun-07	3	301-T8	46
8-Jun-07	4	301-T8	-103
8-Jun-07	5	301-T8	-230
8-Jun-07	6	301-T8	-188
8-Jun-07	7	301-T8	-109
8-Jun-07	8	107-T6	-251
8-Jun-07	9	107-T6	-254
8-Jun-07	10	107-T6	-266
8-Jun-07	11	107-T6	-208
8-Jun-07	12	107-T6	-99
8-Jun-07	13	107-T6	32
8-Jun-07	14	105-T1	470

**Appendix D. Continued.**

Sampling date	ID	Treatment	Eh, mV
8-Jun-07	15	105-T1	530
8-Jun-07	16	105-T1	285
8-Jun-07	17	105-T1	455
8-Jun-07	18	105-T1	477
8-Jun-07	19	105-T1	483
10-Jul-07	1	301-T8	38
10-Jul-07	2	301-T8	30
10-Jul-07	3	301-T8	-10
10-Jul-07	4	301-T8	-156
10-Jul-07	5	301-T8	-229
10-Jul-07	6	301-T8	-170
10-Jul-07	7	301-T8	-96
10-Jul-07	8	107-T6	-269
10-Jul-07	9	107-T6	-289
10-Jul-07	10	107-T6	-265
10-Jul-07	11	107-T6	-238
10-Jul-07	12	107-T6	-220
10-Jul-07	13	107-T6	102
10-Jul-07	14	105-T1	438
10-Jul-07	15	105-T1	570
10-Jul-07	16	105-T1	275
10-Jul-07	17	105-T1	428
10-Jul-07	18	105-T1	500
10-Jul-07	19	105-T1	533
9-Aug-07	1	301-T8	0
9-Aug-07	2	301-T8	-162
9-Aug-07	3	301-T8	-275
9-Aug-07	4	301-T8	-580
9-Aug-07	5	301-T8	-235
9-Aug-07	6	301-T8	-159
9-Aug-07	7	301-T8	-127
9-Aug-07	8	107-T6	-278
9-Aug-07	9	107-T6	-296
9-Aug-07	10	107-T6	130
9-Aug-07	11	107-T6	-250
9-Aug-07	12	107-T6	-271
9-Aug-07	13	107-T6	74

**Appendix D. Continued.**

Sampling date	ID	Treatment	Eh, mV
9-Aug-07	14	105-T1	328
9-Aug-07	15	105-T1	545
9-Aug-07	16	105-T1	325
9-Aug-07	17	105-T1	475
9-Aug-07	18	105-T1	455
9-Aug-07	19	105-T1	537
28-Dec-08	1	301-T8	43
28-Dec-08	2	301-T8	-446
28-Dec-08	3	301-T8	-430
28-Dec-08	4	301-T8	-415
28-Dec-08	5	301-T8	-308
28-Dec-08	6	301-T8	-210
28-Dec-08	7	301-T8	14
28-Dec-08	8	107-T6	350
28-Dec-08	9	107-T6	89
28-Dec-08	10	107-T6	309
28-Dec-08	11	107-T6	258
28-Dec-08	12	107-T6	288
28-Dec-08	13	107-T6	365
28-Dec-08	14	105-T1	598
28-Dec-08	15	105-T1	564
28-Dec-08	16	105-T1	510
28-Dec-08	17	105-T1	570
28-Dec-08	18	105-T1	505
28-Dec-08	19	105-T1	417

**Appendix E. Emissions of N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> determined by incubation chamber method throughout the study (October 2006-April 2009).**

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
6-Oct-06	1	105-T1	2.021158		
6-Oct-06	2	105-T1	1.015538		
6-Oct-06	3	105-T1	0.82273		
6-Oct-06	4	105-T1	0.587233		
6-Oct-06	11	402-T4	2.021158		
6-Oct-06	12	402-T4	1.015538		
6-Oct-06	13	402-T4	0.82273		
6-Oct-06	14	402-T4	0.587233		
6-Oct-06	21	401-T6	18.40744		
6-Oct-06	22	401-T6	22.11637		
6-Oct-06	23	401-T6	13.17421		
6-Oct-06	24	401-T6	4.219169		
6-Oct-06	25	401-T6	8.438646		
6-Oct-06	26	107-T6	14.27728		
6-Oct-06	27	107-T6	17.72737		
6-Oct-06	28	107-T6	9.825138		
6-Oct-06	29	107-T6	14.88065		
6-Oct-06	30	107-T6	10.34147		
6-Oct-06	31	408-T8	5.404599		
6-Oct-06	32	408-T8	18.65266		
6-Oct-06	33	408-T8	7.321037		
6-Oct-06	34	408-T8	12.94814		
6-Oct-06	35	408-T8	15.83896		
6-Oct-06	36	301-T8	4.970134		
6-Oct-06	37	301-T8	11.91997		
6-Oct-06	38	301-T8	18.21592		
6-Oct-06	39	301-T8	17.01361		
6-Oct-06	40	301-T8	8.539978		
3-Nov-06	1	105-T1	0.462431		
3-Nov-06	2	105-T1	0.582366		
3-Nov-06	3	105-T1	0.206853		
3-Nov-06	4	105-T1	0.206298		
3-Nov-06	11	402-T4	0.462431		
3-Nov-06	12	402-T4	0.582366		
3-Nov-06	13	402-T4	0.206853		
3-Nov-06	14	402-T4	0.206298		
3-Nov-06	21	401-T6	12.27066		



## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
3-Nov-06	22	401-T6	9.302216		
3-Nov-06	23	401-T6	11.77361		
3-Nov-06	24	401-T6	4.024451		
3-Nov-06	25	401-T6	7.438508		
3-Nov-06	26	107-T6	1.976313		
3-Nov-06	27	107-T6	6.07105		
3-Nov-06	28	107-T6	4.763343		
3-Nov-06	29	107-T6	3.650601		
3-Nov-06	30	107-T6	3.587276		
3-Nov-06	31	408-T8	0.721028		
3-Nov-06	32	408-T8	3.071622		
3-Nov-06	33	408-T8	0.636944		
3-Nov-06	34	408-T8	2.570814		
3-Nov-06	35	408-T8	2.30883		
3-Nov-06	36	301-T8	1.995717		
3-Nov-06	37	301-T8	1.44452		
3-Nov-06	38	301-T8	2.538598		
3-Nov-06	39	301-T8	4.194898		
3-Nov-06	40	301-T8	2.894338		
15-Dec-06	1	105-T1	0.766643		
15-Dec-06	2	105-T1			
15-Dec-06	3	105-T1	0.155509		
15-Dec-06	4	105-T1	0.237499		
15-Dec-06	11	402-T4	0.766643		
15-Dec-06	12	402-T4			
15-Dec-06	13	402-T4	0.155509		
15-Dec-06	14	402-T4	0.237499		
15-Dec-06	21	401-T6	7.877316		
15-Dec-06	22	401-T6	6.795127		
15-Dec-06	23	401-T6	5.52284		
15-Dec-06	24	401-T6	6.747941		
15-Dec-06	25	401-T6	10.01545		
15-Dec-06	26	107-T6	9.862992		
15-Dec-06	27	107-T6	7.744136		
15-Dec-06	28	107-T6	5.762095		
15-Dec-06	29	107-T6	6.88919		
15-Dec-06	30	107-T6	9.212557		

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
15-Dec-06	31	408-T8	0.643628		
15-Dec-06	32	408-T8	2.410439		
15-Dec-06	33	408-T8	0.472133		
15-Dec-06	34	408-T8	1.015815		
15-Dec-06	35	408-T8	2.703963		
15-Dec-06	36	301-T8	0.744898		
15-Dec-06	37	301-T8	1.350056		
15-Dec-06	38	301-T8	1.041933		
15-Dec-06	39	301-T8	3.440329		
15-Dec-06	40	301-T8	3.919084		
5-Jan-07	1	105-T1	0.647786		
5-Jan-07	2	105-T1	0.218926		
5-Jan-07	3	105-T1	0.424178		
5-Jan-07	4	105-T1	0.351366		
5-Jan-07	11	402-T4	0.647786		
5-Jan-07	12	402-T4	0.218926		
5-Jan-07	13	402-T4	0.424178		
5-Jan-07	14	402-T4	0.351366		
5-Jan-07	21	401-T6	1.52922		
5-Jan-07	22	401-T6	1.392591		
5-Jan-07	23	401-T6	1.486593		
5-Jan-07	24	401-T6	1.583182		
5-Jan-07	25	401-T6	2.235402		
5-Jan-07	26	107-T6	2.265648		
5-Jan-07	27	107-T6	1.828226		
5-Jan-07	28	107-T6	1.669606		
5-Jan-07	29	107-T6	1.261999		
5-Jan-07	30	107-T6	1.685191		
5-Jan-07	31	408-T8	0.763039		
5-Jan-07	32	408-T8	1.622667		
5-Jan-07	33	408-T8	0.772587		
5-Jan-07	34	408-T8	0.963855		
5-Jan-07	35	408-T8	1.860012		
5-Jan-07	36	301-T8	0.068561		
5-Jan-07	37	301-T8	1.017078		
5-Jan-07	38	301-T8	1.606282		
5-Jan-07	39	301-T8	1.881326		

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
5-Jan-07	40	301-T8	2.045859		
9-Feb-07	1	105-T1	0.290506		
9-Feb-07	2	105-T1	0.236729		
9-Feb-07	3	105-T1	0.35574		
9-Feb-07	4	105-T1	0.16749		
9-Feb-07	11	402-T4	0.290506		
9-Feb-07	12	402-T4	0.236729		
9-Feb-07	13	402-T4	0.35574		
9-Feb-07	14	402-T4	0.16749		
9-Feb-07	21	401-T6	0.95289		
9-Feb-07	22	401-T6	0.89745		
9-Feb-07	23	401-T6	1.108862		
9-Feb-07	24	401-T6	1.108492		
9-Feb-07	25	401-T6	1.536058		
9-Feb-07	26	107-T6	1.582011		
9-Feb-07	27	107-T6	1.289042		
9-Feb-07	28	107-T6	1.287009		
9-Feb-07	29	107-T6	0.747578		
9-Feb-07	30	107-T6	1.00753		
9-Feb-07	31	408-T8	0.582674		
9-Feb-07	32	408-T8	0.974019		
9-Feb-07	33	408-T8	0.641441		
9-Feb-07	34	408-T8	0.791806		
9-Feb-07	35	408-T8	0.962438		
9-Feb-07	36	301-T8	0.370955		
9-Feb-07	37	301-T8	0.457688		
9-Feb-07	38	301-T8	1.760528		
9-Feb-07	39	301-T8	0.572387		
9-Feb-07	40	301-T8	0.381304		
2-Mar-07	1	105-T1	0.41235		
2-Mar-07	2	105-T1	0.38229		
2-Mar-07	3	105-T1	0.348102		
2-Mar-07	4	105-T1	0.319396		
2-Mar-07	11	402-T4	0.355678		
2-Mar-07	12	402-T4	0.337876		
2-Mar-07	13	402-T4	0.327958		
2-Mar-07	14	402-T4	0.32956		

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
2-Mar-07	21	401-T6	0.699591		
2-Mar-07	22	401-T6	1.000261		
2-Mar-07	23	401-T6	0.700146		
2-Mar-07	24	401-T6	0.651666		
2-Mar-07	25	401-T6	0.92209		
2-Mar-07	26	107-T6	1.521458		
2-Mar-07	27	107-T6	0.82852		
2-Mar-07	28	107-T6	0.673781		
2-Mar-07	29	107-T6	0.775482		
2-Mar-07	30	107-T6	0.39153		
2-Mar-07	31	408-T8	0.47894		
2-Mar-07	32	408-T8	0.673842		
2-Mar-07	33	408-T8	1.283436		
2-Mar-07	34	408-T8	0.773758		
2-Mar-07	35	408-T8	0.69799		
2-Mar-07	36	301-T8	0.37613		
2-Mar-07	37	301-T8	0.333872		
2-Mar-07	38	301-T8	0.397135		
2-Mar-07	39	301-T8	0.34958		
2-Mar-07	40	301-T8	0.619881		
5-Mar-07	1	105-T1	0.62832		
5-Mar-07	2	105-T1	1.015661		
5-Mar-07	3	105-T1	0.591976		
5-Mar-07	4	105-T1	0.409024		
5-Mar-07	11	402-T4	0.450358		
5-Mar-07	12	402-T4	0.58212		
5-Mar-07	13	402-T4	0.482205		
5-Mar-07	14	402-T4	0.45005		
5-Mar-07	21	401-T6	1.283005		
5-Mar-07	22	401-T6	3.219832		
5-Mar-07	23	401-T6	2.069206		
5-Mar-07	24	401-T6	5.177603		
5-Mar-07	25	401-T6	1.668128		
5-Mar-07	26	107-T6	2.785244		
5-Mar-07	27	107-T6	2.129943		
5-Mar-07	28	107-T6	1.315037		
5-Mar-07	29	107-T6	1.404049		

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
5-Mar-07	30	107-T6	1.08761		
5-Mar-07	31	408-T8	1.140031		
5-Mar-07	32	408-T8	1.175205		
5-Mar-07	33	408-T8	0.840963		
5-Mar-07	34	408-T8	1.149518		
5-Mar-07	35	408-T8	1.682727		
5-Mar-07	36	301-T8	0.750226		
5-Mar-07	37	301-T8	0.588834		
5-Mar-07	38	301-T8	1.465587		
5-Mar-07	39	301-T8	0.428243		
5-Mar-07	40	301-T8	1.023484		
23-Mar-07	1	105-T1	0.204635		
23-Mar-07	2	105-T1	0.150674		
23-Mar-07	3	105-T1	0.292785		
23-Mar-07	4	105-T1	0.020821		
23-Mar-07	11	402-T4			
23-Mar-07	12	402-T4			
23-Mar-07	13	402-T4			
23-Mar-07	14	402-T4			
23-Mar-07	21	401-T6	2.986491		
23-Mar-07	22	401-T6	4.105578		
23-Mar-07	23	401-T6	4.93416		
23-Mar-07	24	401-T6	5.192942		
23-Mar-07	25	401-T6	8.5855		
23-Mar-07	26	107-T6	3.503254		
23-Mar-07	27	107-T6	1.928758		
23-Mar-07	28	107-T6	1.854283		
23-Mar-07	29	107-T6	2.111155		
23-Mar-07	30	107-T6	1.070238		
23-Mar-07	31	408-T8	0.388819		
23-Mar-07	32	408-T8	0.884822		
23-Mar-07	33	408-T8	0.471486		
23-Mar-07	34	408-T8	0.917162		
23-Mar-07	35	408-T8	0.86585		
23-Mar-07	36	301-T8	0.659736		
23-Mar-07	37	301-T8	0.384569		
23-Mar-07	38	301-T8	1.853975		

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
23-Mar-07	39	301-T8	0.297343		
23-Mar-07	40	301-T8	0.569923		
13-Apr-07	1	105-T1	0.169		
13-Apr-07	2	105-T1	0.17325		
13-Apr-07	3	105-T1	0.060645		
13-Apr-07	4	105-T1	0.059228		
13-Apr-07	11	402-T4	0.643012		
13-Apr-07	12	402-T4	0.285424		
13-Apr-07	13	402-T4	0.224994		
13-Apr-07	14	402-T4	0.238916		
13-Apr-07	21	401-T6	3.965839		
13-Apr-07	22	401-T6	5.462657		
13-Apr-07	23	401-T6	6.39214		
13-Apr-07	24	401-T6	1.698712		
13-Apr-07	25	401-T6	11.82976		
13-Apr-07	26	107-T6	1.430506		
13-Apr-07	27	107-T6	1.476152		
13-Apr-07	28	107-T6	2.926462		
13-Apr-07	29	107-T6	3.338258		
13-Apr-07	30	107-T6	2.383088		
13-Apr-07	31	408-T8	0.801508		
13-Apr-07	32	408-T8	0.945036		
13-Apr-07	33	408-T8	0.607715		
13-Apr-07	34	408-T8	1.326587		
13-Apr-07	35	408-T8	2.458918		
13-Apr-07	36	301-T8			
13-Apr-07	37	301-T8	0.640424		
13-Apr-07	38	301-T8	3.953026		
13-Apr-07	39	301-T8	0.509093		
13-Apr-07	40	301-T8	1.182812		
11-May-07	1	105-T1	0.380134		
11-May-07	2	105-T1	0.43003		
11-May-07	3	105-T1	0.129052		
11-May-07	4	105-T1	0.352167		
11-May-07	11	402-T4	0.124925		
11-May-07	12	402-T4	0.079156		
11-May-07	13	402-T4	0.217879		

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
11-May-07	14	402-T4	0.267098		
11-May-07	21	401-T6	11.28376		
11-May-07	22	401-T6	9.796618		
11-May-07	23	401-T6	10.0124		
11-May-07	24	401-T6			
11-May-07	25	401-T6	13.86197		
11-May-07	26	107-T6	5.460347		
11-May-07	27	107-T6	4.927322		
11-May-07	28	107-T6			
11-May-07	29	107-T6	7.007924		
11-May-07	30	107-T6	6.128522		
11-May-07	31	408-T8	0.695957		
11-May-07	32	408-T8	0.864987		
11-May-07	33	408-T8	0.388018		
11-May-07	34	408-T8	1.26471		
11-May-07	35	408-T8	1.308692		
11-May-07	36	301-T8			
11-May-07	37	301-T8	1.087117		
11-May-07	38	301-T8	4.966562		
11-May-07	39	301-T8	1.8711		
11-May-07	40	301-T8	1.163932		
8-Jun-07	1	105-T1			
8-Jun-07	2	105-T1	0.255548		
8-Jun-07	3	105-T1	0.076476		
8-Jun-07	4	105-T1	0.001201		
8-Jun-07	11	402-T4	1.835588		
8-Jun-07	12	402-T4	0.15902		
8-Jun-07	13	402-T4	0.235035		
8-Jun-07	14	402-T4	0.102225		
8-Jun-07	21	401-T6	18.33823		
8-Jun-07	22	401-T6	11.22115		
8-Jun-07	23	401-T6	8.683906		
8-Jun-07	24	401-T6			
8-Jun-07	25	401-T6	18.66877		
8-Jun-07	26	107-T6	7.023416		
8-Jun-07	27	107-T6			
8-Jun-07	28	107-T6			

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
8-Jun-07	29	107-T6	8.755485		
8-Jun-07	30	107-T6	1.332993		
8-Jun-07	31	408-T8	1.333794		
8-Jun-07	32	408-T8	2.692998		
8-Jun-07	33	408-T8	0.95982		
8-Jun-07	34	408-T8			
8-Jun-07	35	408-T8	1.837374		
8-Jun-07	36	301-T8			
8-Jun-07	37	301-T8	1.608715		
8-Jun-07	38	301-T8	5.921392		
8-Jun-07	39	301-T8	1.853144		
8-Jun-07	40	301-T8	2.166441		
10-Jul-07	1	105-T1	0.466959		
10-Jul-07	2	105-T1	0.350596		
10-Jul-07	3	105-T1	0.120089		
10-Jul-07	4	105-T1			
10-Jul-07	11	402-T4	0.001756		
10-Jul-07	12	402-T4	0.046662		
10-Jul-07	13	402-T4	0.118056		
10-Jul-07	14	402-T4	0.327004		
10-Jul-07	21	401-T6	33.69646		
10-Jul-07	22	401-T6	21.55399		
10-Jul-07	23	401-T6	35.55925		
10-Jul-07	24	401-T6	16.31664		
10-Jul-07	25	401-T6	41.76625		
10-Jul-07	26	107-T6	21.16019		
10-Jul-07	27	107-T6	24.93442		
10-Jul-07	28	107-T6	6.720776		
10-Jul-07	29	107-T6	23.84983		
10-Jul-07	30	107-T6	3.642008		
10-Jul-07	31	408-T8	1.672656		
10-Jul-07	32	408-T8	2.862583		
10-Jul-07	33	408-T8	3.435709		
10-Jul-07	34	408-T8	3.184381		
10-Jul-07	35	408-T8	2.676181		
10-Jul-07	36	301-T8	2.1248		
10-Jul-07	37	301-T8	1.911171		



## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
10-Jul-07	38	301-T8	5.66144		
10-Jul-07	39	301-T8	3.438604		
10-Jul-07	40	301-T8	3.197317		
10-Aug-07	1	105-T1	0.501208		
10-Aug-07	2	105-T1	0.207561		
10-Aug-07	3	105-T1	0.102102		
10-Aug-07	4	105-T1	0.048202		
10-Aug-07	11	402-T4	0.034157		
10-Aug-07	12	402-T4	0.047956		
10-Aug-07	13	402-T4	0.115284		
10-Aug-07	14	402-T4	0.13592		
10-Aug-07	21	401-T6	27.31717		
10-Aug-07	22	401-T6	25.04665		
10-Aug-07	23	401-T6	30.25955		
10-Aug-07	24	401-T6	23.8911		
10-Aug-07	25	401-T6	14.32622		
10-Aug-07	26	107-T6	18.98761		
10-Aug-07	27	107-T6	19.39245		
10-Aug-07	28	107-T6	19.34181		
10-Aug-07	29	107-T6	23.67741		
10-Aug-07	30	107-T6	24.14464		
10-Aug-07	31	408-T8	0.871486		
10-Aug-07	32	408-T8	2.236788		
10-Aug-07	33	408-T8	1.14616		
10-Aug-07	34	408-T8	1.5712		
10-Aug-07	35	408-T8	3.652911		
10-Aug-07	36	301-T8	1.975543		
10-Aug-07	37	301-T8	1.767766		
10-Aug-07	38	301-T8	7.786086		
10-Aug-07	39	301-T8	3.907011		
10-Aug-07	40	301-T8	2.796178		
7-Sep-07	1	105-T1	0.322106		
7-Sep-07	2	105-T1	0.309786		
7-Sep-07	3	105-T1	0.011827		
7-Sep-07	4	105-T1			
7-Sep-07	11	402-T4			
7-Sep-07	12	402-T4	0.006714		

**Appendix E. Continued.**

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
7-Sep-07	13	402-T4	0.150304		
7-Sep-07	14	402-T4	0.105459		
7-Sep-07	21	401-T6	41.96038		
7-Sep-07	22	401-T6			
7-Sep-07	23	401-T6			
7-Sep-07	24	401-T6	46.90249		
7-Sep-07	25	401-T6	41.00891		
7-Sep-07	26	107-T6			
7-Sep-07	27	107-T6	21.29543		
7-Sep-07	28	107-T6	8.02377		
7-Sep-07	29	107-T6			
7-Sep-07	30	107-T6	8.575706		
7-Sep-07	31	408-T8	0.247139		
7-Sep-07	32	408-T8	2.132469		
7-Sep-07	33	408-T8	0.438592		
7-Sep-07	34	408-T8	2.144666		
7-Sep-07	35	408-T8	3.284204		
7-Sep-07	36	301-T8	2.368397		
7-Sep-07	37	301-T8	2.048878		
7-Sep-07	38	301-T8	6.211498		
7-Sep-07	39	301-T8	3.826284		
7-Sep-07	40	301-T8	2.905179		
2-May-08	1	105-T1	0.016509		
2-May-08	2	105-T1	0.00961		
2-May-08	3	105-T1			
2-May-08	4	105-T1	0.565858		
2-May-08	11	402-T4	1.086686		
2-May-08	12	402-T4	0.800369		
2-May-08	13	402-T4	0.468591		
2-May-08	14	402-T4	0.674212		
2-May-08	15	202-T4	2.128711		
2-May-08	16	202-T4	1.128081		
2-May-08	17	202-T4	2.866802		
2-May-08	18	202-T4	0.857595		
2-May-08	19	202-T4	0.568691		
2-May-08	21	401-T6	16.1846		
2-May-08	22	401-T6	18.58195		

**Appendix E. Continued.**

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
2-May-08	23	401-T6	13.75583		
2-May-08	24	401-T6	13.38291		
2-May-08	25	401-T6	10.74224		
2-May-08	26	107-T6	9.99189		
2-May-08	27	107-T6	10.24587		
2-May-08	28	107-T6	19.92082		
2-May-08	29	107-T6	2.815428		
2-May-08	30	107-T6	13.12419		
2-May-08	31	408-T8	0.953322		
2-May-08	32	408-T8	1.010671		
2-May-08	33	408-T8	0.98831		
2-May-08	34	408-T8	1.479632		
2-May-08	35	408-T8	1.753629		
2-May-08	36	301-T8	1.068021		
2-May-08	37	301-T8	1.71556		
2-May-08	38	301-T8			
2-May-08	39	301-T8	0.794578		
2-May-08	40	301-T8	1.41717		
5-Jun-08	1	105-T1	0.123754		
5-Jun-08	2	105-T1	0.151228		
5-Jun-08	3	105-T1	0.105459		
5-Jun-08	4	105-T1	0.052976		
5-Jun-08	5	105-T1	0.072318		
5-Jun-08	6	404-T1	0.834064		
5-Jun-08	7	404-T1	1.869622		
5-Jun-08	8	404-T1	0.193424		
5-Jun-08	9	404-T1	0.293894		
5-Jun-08	10	404-T1	0.307014		
5-Jun-08	11	402-T4	1.474458		
5-Jun-08	12	402-T4	1.664124		
5-Jun-08	13	402-T4	1.176129		
5-Jun-08	14	402-T4	1.773649		
5-Jun-08	15	202-T4	0.801539		
5-Jun-08	16	202-T4	0.364179		
5-Jun-08	17	202-T4	0.70495		
5-Jun-08	18	202-T4	0.717825		
5-Jun-08	19	202-T4	0.689982		

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
5-Jun-08	21	401-T6	11.76874		
5-Jun-08	22	401-T6	15.8981		
5-Jun-08	23	401-T6	12.90403		
5-Jun-08	24	401-T6	12.36823		
5-Jun-08	25	401-T6	10.99578		
5-Jun-08	26	107-T6	6.313076		
5-Jun-08	27	107-T6	4.131882		
5-Jun-08	28	107-T6	13.29488		
5-Jun-08	29	107-T6	4.574046		
5-Jun-08	30	107-T6			
5-Jun-08	31	408-T8	0.396704		
5-Jun-08	32	408-T8	1.246414		
5-Jun-08	33	408-T8	1.114714		
5-Jun-08	34	408-T8	1.57351		
5-Jun-08	35	408-T8	1.260706		
5-Jun-08	36	301-T8	1.731946		
5-Jun-08	37	301-T8	1.312758		
5-Jun-08	38	301-T8	2.504594		
5-Jun-08	39	301-T8	3.244903		
5-Jun-08	40	301-T8	9.118833		
11-Jul-08	1	105-T1	0.283791		
11-Jul-08	2	105-T1	0.390236		
11-Jul-08	3	105-T1	0.125664		
11-Jul-08	4	105-T1	0.093817		
11-Jul-08	5	105-T1	0.262847		
11-Jul-08	6	404-T1	0.083714		
11-Jul-08	7	404-T1	0.499638		
11-Jul-08	8	404-T1	0.147902		
11-Jul-08	9	404-T1	0.065604		
11-Jul-08	10	404-T1	0.187634		
11-Jul-08	11	402-T4	1.447785		
11-Jul-08	12	402-T4	0.952521		
11-Jul-08	13	402-T4	0.968598		
11-Jul-08	14	402-T4	1.215183		
11-Jul-08	15	202-T4	0.083714		
11-Jul-08	16	202-T4	0.499638		
11-Jul-08	17	202-T4	0.147902		

**Appendix E. Continued.**

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
11-Jul-08	18	202-T4	0.065604		
11-Jul-08	19	202-T4	0.187634		
11-Jul-08	21	401-T6	44.54961		
11-Jul-08	22	401-T6	42.30214		
11-Jul-08	23	401-T6	44.05306		
11-Jul-08	24	401-T6	36.97823		
11-Jul-08	25	401-T6	53.34511		
11-Jul-08	26	107-T6	19.05282		
11-Jul-08	27	107-T6	33.63773		
11-Jul-08	28	107-T6	32.29214		
11-Jul-08	29	107-T6	11.03256		
11-Jul-08	30	107-T6	30.93367		
11-Jul-08	31	408-T8	1.068082		
11-Jul-08	32	408-T8	3.030782		
11-Jul-08	33	408-T8	3.91776		
11-Jul-08	34	408-T8	9.799205		
11-Jul-08	35	408-T8	4.020509		
11-Jul-08	36	301-T8	1.529466		
11-Jul-08	37	301-T8	2.315298		
11-Jul-08	38	301-T8	2.651264		
11-Jul-08	39	301-T8	3.290734		
11-Jul-08	40	301-T8	4.877057		
26-Sep-08	1	105-T1	0.352906		
26-Sep-08	2	105-T1	0.285947		
26-Sep-08	3	105-T1	0.058766		
26-Sep-08	4	105-T1	0.197366		
26-Sep-08	5	105-T1	0.207222		
26-Sep-08	6	404-T1	0.452021		
26-Sep-08	7	404-T1	1.310355		
26-Sep-08	8	404-T1	0.328636		
26-Sep-08	9	404-T1	0.589574		
26-Sep-08	10	404-T1	0.056056		
26-Sep-08	11	402-T4	0.405574		
26-Sep-08	12	402-T4	0.221144		
26-Sep-08	13	402-T4	0.126157		
26-Sep-08	14	402-T4	1.425424		
26-Sep-08	15	202-T4	0.452021		

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
26-Sep-08	16	202-T4	1.310355		
26-Sep-08	17	202-T4	0.328636		
26-Sep-08	18	202-T4	0.60177		
26-Sep-08	19	202-T4	0.056056		
26-Sep-08	21	401-T6	42.87483		
26-Sep-08	22	401-T6	47.25669		
26-Sep-08	23	401-T6	45.08085		
26-Sep-08	24	401-T6	54.70197		
26-Sep-08	25	401-T6	36.71588		
26-Sep-08	26	107-T6	21.47542		
26-Sep-08	27	107-T6	16.06577		
26-Sep-08	28	107-T6	23.57352		
26-Sep-08	29	107-T6	5.798654		
26-Sep-08	30	107-T6	13.18622		
26-Sep-08	31	408-T8	1.967566		
26-Sep-08	32	408-T8	2.685575		
26-Sep-08	33	408-T8	4.010776		
26-Sep-08	34	408-T8	1.028658		
26-Sep-08	35	408-T8	4.172168		
26-Sep-08	36	301-T8	4.182332		
26-Sep-08	37	301-T8	6.451922		
26-Sep-08	38	301-T8	2.852942		
26-Sep-08	39	301-T8	4.342738		
26-Sep-08	40	301-T8	8.179864		
23-Oct-08	1	105-T1	0.288781		
23-Oct-08	2	105-T1	0.322599		
23-Oct-08	3	105-T1	0.057504		
23-Oct-08	4	105-T1	0.087626		
23-Oct-08	5	105-T1	0.091599		
23-Oct-08	6	404-T1	0.049834		
23-Oct-08	7	404-T1	0.009825		
23-Oct-08	8	404-T1	0.084115		
23-Oct-08	9	404-T1	0.021652		
23-Oct-08	10	404-T1	0.246		
23-Oct-08	11	402-T4	0.102687		
23-Oct-08	12	402-T4	0.408439		
23-Oct-08	13	402-T4	0.479864		

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
23-Oct-08	14	402-T4	0.404928		
23-Oct-08	15	202-T4	0.221329		
23-Oct-08	16	202-T4	0.282867		
23-Oct-08	17	202-T4	1.025763		
23-Oct-08	18	202-T4	0.920982		
23-Oct-08	19	202-T4	0.989727		
23-Oct-08	21	401-T6	6.480782		
23-Oct-08	22	401-T6	8.158489		
23-Oct-08	23	401-T6	9.861606		
23-Oct-08	24	401-T6	7.273851		
23-Oct-08	25	401-T6	9.70776		
23-Oct-08	26	107-T6	9.216192		
23-Oct-08	27	107-T6	7.318665		
23-Oct-08	28	107-T6	8.064888		
23-Oct-08	29	107-T6	5.116681		
23-Oct-08	30	107-T6	7.129338		
23-Oct-08	31	408-T8			
23-Oct-08	32	408-T8	0.602571		
23-Oct-08	33	408-T8	1.10726		
23-Oct-08	34	408-T8	7.450335		
23-Oct-08	35	408-T8	4.519222		
23-Oct-08	36	301-T8	2.516268		
23-Oct-08	37	301-T8	2.774064		
23-Oct-08	38	301-T8	2.850571		
23-Oct-08	39	301-T8	3.614811		
23-Oct-08	40	301-T8	7.626172		
28-Dec-08	1	105-T1	0.141126	-4.06498	17.78638
28-Dec-08	2	105-T1	0.305598	-6.07653	18.16214
28-Dec-08	3	105-T1	0.126249	-0.10133	15.94947
28-Dec-08	4	105-T1	0.16016	3.720948	-29.8477
28-Dec-08	5	105-T1	0.164133	1.28744	8.973888
28-Dec-08	6	404-T1	0.188712	-4.91352	52.39203
28-Dec-08	7	404-T1	0.180211	-1.54062	94.99706
28-Dec-08	8	404-T1	0.151474	-0.06068	20.85037
28-Dec-08	9	404-T1	0.190005	1.5631	-14.1212
28-Dec-08	10	404-T1	0.144452	3.337796	8.484784
28-Dec-08	11	402-T4	0.182244	-7.01501	48.96338

## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
28-Dec-08	12	402-T4	0.173373	4.917528	33.83072
28-Dec-08	13	402-T4	0.290998	4.647104	74.79349
28-Dec-08	14	402-T4	0.235374	0.221452	48.11946
28-Dec-08	15	202-T4	0.556556	-5.15992	24.04125
28-Dec-08	16	202-T4	0.209686	-5.13374	-3.25987
28-Dec-08	17	202-T4	0.730915	3.738504	43.09413
28-Dec-08	18	202-T4	0.686008	2.640176	29.55198
28-Dec-08	19	202-T4	0.320382	1.923768	266.0295
28-Dec-08	21	401-T6	6.922916	4.588584	135.5311
28-Dec-08	22	401-T6	7.779649	3.225684	85.11888
28-Dec-08	23	401-T6	5.415502	2.012472	93.41147
28-Dec-08	24	401-T6	8.9705	3.23246	86.67736
28-Dec-08	25	401-T6	6.839386	-6.89181	66.0389
28-Dec-08	26	107-T6	9.735295	2.697772	94.81965
28-Dec-08	27	107-T6	6.624002	3.468388	89.89165
28-Dec-08	28	107-T6	3.679214	-0.82636	79.17202
28-Dec-08	29	107-T6	5.882954	2.373448	95.73626
28-Dec-08	30	107-T6	10.81333	4.111492	104.5783
28-Dec-08	31	408-T8	0.575221	3.431428	127.4911
28-Dec-08	32	408-T8	0.447339	3.383072	44.64398
28-Dec-08	33	408-T8	4.134007	2.779084	1287.649
28-Dec-08	34	408-T8	11.52092	5.102636	2645.663
28-Dec-08	35	408-T8	0.725001	3.069528	492.0288
28-Dec-08	36	301-T8	1.314421	-1.22584	197.0461
28-Dec-08	37	301-T8	1.619341	3.65596	198.9236
28-Dec-08	38	301-T8	0.197305	3.47424	-11.2013
28-Dec-08	39	301-T8	1.747869	-0.78848	224.7402
28-Dec-08	40	301-T8	2.12791	3.520132	431.386
8-Apr-09	1	105-T1	0.533548	5.806416	135.074
8-Apr-09	2	105-T1	0.450943	3.062136	59.88752
8-Apr-09	3	105-T1	0.313359	2.147376	47.21886
8-Apr-09	4	105-T1	0.342465	3.667664	55.17635
8-Apr-09	5	105-T1	0.339416	2.069144	19.9005
8-Apr-09	6	404-T1	0.19712	5.303144	78.31578
8-Apr-09	7	404-T1	0.202017	0.162008	55.94142
8-Apr-09	8	404-T1	0.20442	5.458992	81.36374
8-Apr-09	9	404-T1	0.186864	4.199272	88.94301



## Appendix E. Continued.

Sampling date	ID	Treatment	N <sub>2</sub> O, mg m <sup>-2</sup> h <sup>-1</sup>	CH <sub>4</sub> , mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub> , mg m <sup>-2</sup> h <sup>-1</sup>
8-Apr-09	10	404-T1	0.176884	5.475008	76.7228
8-Apr-09	11	402-T4	3.554197	4.859008	107.8246
8-Apr-09	12	402-T4	1.716453	6.45876	35.3313
8-Apr-09	13	402-T4	3.12158	6.905976	171.0225
8-Apr-09	14	402-T4	3.027794	4.63848	97.49678
8-Apr-09	15	202-T4	0.93401	4.86024	96.55677
8-Apr-09	16	202-T4	0.824239	4.394544	137.6477
8-Apr-09	17	202-T4	2.158402	0.838992	74.25387
8-Apr-09	18	202-T4	2.067388	5.357968	142.2073
8-Apr-09	19	202-T4	3.072793	2.536688	96.05904
8-Apr-09	21	401-T6	13.1553	4.485712	98.44912
8-Apr-09	22	401-T6	16.61484	-2.16955	15.97658
8-Apr-09	23	401-T6	8.505174	0.659736	58.52
8-Apr-09	24	401-T6	15.1662	-1.5979	10.63586
8-Apr-09	25	401-T6	12.3309	-1.14268	270.695
8-Apr-09	26	107-T6	13.01734	1.76792	134.3213
8-Apr-09	27	107-T6	9.20612	3.388616	222.1653
8-Apr-09	28	107-T6	7.80201	2.378992	50.36786
8-Apr-09	29	107-T6	10.13003	1.402632	138.5458
8-Apr-09	30	107-T6	39.07322	3.693536	99.86838
8-Apr-09	31	408-T8	0.681573	-0.20451	53.60062
8-Apr-09	32	408-T8	0.5548	4.269496	189.0048
8-Apr-09	33	408-T8	2.974664	4.467232	808.6121
8-Apr-09	34	408-T8	11.13756	3.76376	2422.265
8-Apr-09	35	408-T8	2.277598	5.466384	283.2824
8-Apr-09	36	301-T8	1.207329	4.85408	293.715
8-Apr-09	37	301-T8	1.472979	6.73904	288.9755
8-Apr-09	38	301-T8	0.334334	6.009696	-2.38638
8-Apr-09	39	301-T8	1.685684	-3.33749	173.6171
8-Apr-09	40	301-T8	1.380025	7.116648	288.7907

**Appendix F. Numerical order of leachate sampling dates, used in Appendices G and F.**

Sampling time	Sampling date
1	7/14/2006
2	8/10/2006
3	9/8/2006
4	10/6/2006
5	11/3/2006
6	12/1/2006
7	12/15/2006
8	1/5/2007
9	1/19/2007
10	2/9/2007
11	3/2/2007
12	3/23/2007
13	4/13/2007
14	5/11/2007
15	6/8/2007
16	7/10/2007
17	8/9/2007
18	9/7/2007
19	10/12/2007
20	1/23/2008
21	3/24/2008
22	5/2/2008
23	6/5/2008
24	7/11/2008
25	9/18/2008
26	10/23/2008
27	12/4/2008
28	12/28/2008

**Appendix G. Differences of least squares means in time series analysis for N and P forms, pH, EC and DO for each sampling event throughout the study (July 2006-December 2008).**

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
			p-values								
1	1	2	0.6957	0.0246	0.7358	0.8474	0.8673	0.8826	0.8771		0.864
1	1	3	0.9367	0.0415	0.7036	0.8087	0.806	0.7345	0.9645		0.8018
1	1	4	0.493	0.0105	0.7746	0.8603	0.7261	0.9005	0.6952		0.7228
1	1	5	0.4139	0.0816	0.1978	0.3043	0.2895	0.1069	0.4451		0.295
1	1	6	0.5455	0.9898	0.8633	0.7361	0.9219	0.2375	0.8387		0.9198
1	2	3	0.6527	0.8395	0.9352	0.9324	0.8987	0.781	0.8812		0.897
1	2	4	0.643	0.6299	0.9364	0.5611	0.7717	0.9736	0.7243		0.7715
1	2	5	0.1479	<.0001	0.0448	0.1315	0.1316	0.0524	0.4117		0.1344
1	2	6	0.1543	0.0013	0.8248	0.4496	0.7213	0.1292	0.9412		0.7144
1	3	4	0.3795	0.5166	0.8767	0.5335	0.8877	0.7576	0.6341		0.8891
1	3	5	0.2754	<.0001	0.0463	0.1297	0.1225	0.105	0.3673		0.1248
1	3	6	0.3476	0.0047	0.7779	0.431	0.6561	0.2606	0.8291		0.6485
1	4	5	0.0802	<.0001	0.0508	0.2579	0.0909	0.0493	0.5803		0.093
1	4	6	0.0672	0.0003	0.8812	0.8024	0.5518	0.121	0.7847		0.5454
1	5	6	0.7166	0.0324	0.0796	0.3756	0.2586	0.4542	0.4492		0.2656
2	2	3	0.9215	0.9193	0.8112	0.9859	0.8127	0.9681	0.8464		0.8122
2	2	4	0.419	0.4227	0.3603	0.7845	0.7462	0.9684	0.3281		0.7537
2	2	5	<.0001	<.0001	0.0479	0.6765	0.1441	0.6138	0.1803		0.1426
2	2	6	0.0003	<.0001	0.0207	0.368	0.4331	0.9279	0.0328		0.4309
2	2	7	0.4066	0.0434	0.3813	0.8028	0.5307	0.6115	0.7263		0.5321
2	2	8	0.9818	0.0015	0.1541	0.8966	0.7626	0.8298	0.1275		0.7713
2	3	4	0.3683	0.4911	0.506	0.7997	0.9308	0.9987	0.4483		0.9391
2	3	5	0.0001	<.0001	0.0943	0.6945	0.2353	0.5966	0.2836		0.2335
2	3	6	0.0006	<.0001	0.0489	0.3862	0.6327	0.8929	0.0698		0.6306

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
2	3	7	0.4832	0.0634	0.5654	0.8214	0.7361	0.6603	0.9125		0.7383
2	3	8	0.9388	0.0025	0.2438	0.9115	0.948	0.8683	0.2006		0.9576
2	4	5	<.0001	0.0006	0.3542	0.9185	0.2765	0.5824	0.83		0.2692
2	4	6	<.0001	<.0001	0.2469	0.5815	0.714	0.8893	0.3545		0.7018
2	4	7	0.0713	0.2883	0.8226	0.9355	0.8172	0.6449	0.4185		0.8095
2	4	8	0.4013	0.0182	0.6185	0.884	0.9827	0.8623	0.6107		0.9815
2	5	6	0.2547	0.7965	0.8581	0.571	0.2668	0.5721	0.379		0.2656
2	5	7	<.0001	0.0017	0.1381	0.8138	0.2443	0.2068	0.2035		0.2404
2	5	8	<.0001	0.4189	0.7123	0.7859	0.2655	0.4308	0.7132		0.2576
2	6	7	<.0001	<.0001	0.0503	0.3613	0.8544	0.4135	0.0179		0.8475
2	6	8	0.0003	0.2727	0.5825	0.4563	0.6931	0.7128	0.7348		0.6796
2	7	8	0.4159	0.0775	0.406	0.9244	0.7966	0.7768	0.1425		0.7875
3	1	2	0.2889	0.6707	0.7106	0.5756	0.5411	0.748	0.5741		0.5385
3	1	5	0.5114	0.2361	0.2566	0.2825	0.9625	0.4155	0.1599		0.9646
3	1	6	0.0124	0.4228	0.5228	0.148	0.6433	0.457	0.3204		0.6448
3	1	7	0.4859	0.1139	0.0827	0.5062	0.869	0.5052	0.0074		0.8683
3	1	8	0.8445	0.1456	0.1999	0.3219	0.4634	0.5216	0.0515		0.4645
3	2	5	0.0447	0.5519	0.1163	0.7595	0.4441	0.6742	0.4939		0.4395
3	2	6	0.0002	0.8224	0.2736	0.5063	0.7245	0.7282	0.7881		0.719
3	2	7	0.4982	0.3224	0.0322	0.9434	0.5327	0.7854	0.0476		0.53
3	2	8	0.2342	0.3917	0.0869	0.822	0.9328	0.8096	0.2182		0.9272
3	5	6	0.0003	0.4685	0.3395	0.4584	0.3807	0.9014	0.4616		0.3802
3	5	7	0.0134	0.4494	0.2526	0.4747	0.819	0.8121	0.0243		0.8138
3	5	8	0.0926	0.6084	0.7763	0.8667	0.1484	0.7605	0.3317		0.148

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
3	6	7	<.0001	0.1515	0.0425	0.1643	0.5863	0.906	0.0031		0.5903
3	6	8	<.0001	0.2162	0.2153	0.3633	0.5691	0.8564	0.0881		0.5687
3	7	8	0.3491	0.7818	0.3784	0.5742	0.2957	0.9547	0.1854		0.2981
4	1	5	0.125	0.0204	0.0142	0.8991	0.9685	0.5394	0.0751		0.9633
4	1	6	0.0129	0.0527	0.0247	0.7182	0.9772	0.5026	0.1496		0.9727
4	1	7	0.1392	0.0129	0.0045	0.6819	0.9352	0.7003	0.0025		0.9299
4	1	8	0.6009	0.018	0.0082	0.3777	0.8442	0.8062	0.0221		0.8492
4	5	6	0.1302	0.56	0.7655	0.4463	0.9872	0.9266	0.5981		0.9861
4	5	7	<.0001	0.7885	0.5319	0.3954	0.9471	0.7164	0.0484		0.9471
4	5	8	0.0012	0.9418	0.7608	0.1102	0.7088	0.5587	0.4185		0.7086
4	6	7	<.0001	0.3968	0.3609	0.9431	0.936	0.6504	0.013		0.9349
4	6	8	<.0001	0.5126	0.5499	0.421	0.7298	0.5007	0.1837		0.7304
4	7	8	0.1301	0.8452	0.7484	0.4542	0.6602	0.8247	0.2434		0.6598
5	1	5	0.1577	0.0021	0.0026	0.8267	0.4716	0.5671	0.099		0.4672
5	1	6	0.1167	0.0018	0.0032	0.2406	0.2453	0.5925	0.1631		0.2421
5	1	7	0.0634	0.0002	0.0008	0.0483	0.6915	0.6812	0.0058		0.6863
5	1	8	0.3933	0.0005	0.0008	0.1291	0.1264	0.7336	0.0429		0.1244
5	5	6	0.8043	0.933	0.9277	0.1306	0.4837	0.953	0.6855		0.4833
5	5	7	<.0001	0.3205	0.5867	0.0055	0.6092	0.7976	0.0782		0.6088
5	5	8	0.0004	0.4974	0.5869	0.0398	0.2002	0.7128	0.5519		0.1998
5	6	7	<.0001	0.3631	0.5259	0.2035	0.2259	0.8434	0.0304		0.2254
5	6	8	0.0001	0.5521	0.526	0.585	0.5611	0.7571	0.3175		0.5607
5	7	8	0.112	0.7526	0.9998	0.4678	0.0733	0.911	0.2428		0.073
6	1	5	0.9274	0.0034	0.0043	0.5525	0.6624	0.765	0.2868	0.8756	0.6574

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
6	1	6	0.2567	0.0047	0.0047	0.8204	0.889	0.8069	0.3524	0.7471	0.8837
6	1	7	0.1925	0.0019	0.0031	0.112	0.396	0.8596	0.1239	0.4954	0.3919
6	1	8	0.6523	0.0049	0.0122	0.3956	0.3265	0.8141	0.3211	0.0286	0.3228
6	5	6	0.0526	0.8706	0.9557	0.561	0.6383	0.9311	0.8303	0.7927	0.638
6	5	7	0.0552	0.7724	0.869	0.1146	0.5141	0.8463	0.4531	0.4055	0.5136
6	5	8	0.5693	0.8525	0.5724	0.6856	0.3886	0.9194	0.908	0.0013	0.3881
6	6	7	0.0001	0.6511	0.8255	0.031	0.2618	0.9145	0.3348	0.5692	0.2613
6	6	8	0.0123	0.9817	0.6107	0.3241	0.183	0.9882	0.9213	0.0032	0.1825
6	7	8	0.1769	0.6347	0.4658	0.2405	0.8338	0.9262	0.3866	0.0169	0.8337
7	1	5	0.928	0.0121	0.0135	0.7459	0.8442	0.5943	0.1971	0.2365	0.8389
7	1	6	0.0692	0.0244	0.0248	0.6001	0.2154	0.8054	0.4059	0.3407	0.2173
7	1	7	0.8805	0.0238	0.0293	0.2279	0.9596	0.6798	0.2676	0.1497	0.9648
7	1	8	0.9839	0.017	0.0166	0.3684	0.6347	0.5854	0.1361	0.1115	0.6297
7	5	6	0.0026	0.6819	0.721	0.751	0.0233	0.6496	0.4674	0.714	0.0231
7	5	7	0.9243	0.6921	0.6442	0.1624	0.6956	0.849	0.774	0.6835	0.6953
7	5	8	0.8611	0.8463	0.9056	0.3619	0.6592	0.9837	0.7502	0.5175	0.6589
7	6	7	0.0019	0.9889	0.9166	0.2801	0.0602	0.7918	0.6602	0.4389	0.0599
7	6	8	0.0045	0.829	0.8114	0.5521	0.0068	0.635	0.2962	0.3109	0.0067
7	7	8	0.7871	0.8399	0.7314	0.6271	0.4054	0.8331	0.5449	0.8106	0.4049
8	1	5	0.4731	0.0023	0.0015	0.7484	0.2806	0.7343	0.2998	0.3957	0.2772
8	1	6	0.1114	0.0077	0.0038	0.6845	0.5127	0.6574	0.8516	0.3388	0.5081
8	1	7	0.5606	0.0068	0.0942	0.4478	0.1951	0.5263	0.4701	0.3302	0.1924
8	1	8	0.9331	0.0055	0.004	0.5787	0.2024	0.4271	0.7272	0.3544	0.1996
8	5	6	0.0003	0.5372	0.6405	0.8921	0.5014	0.8688	0.1788	0.865	0.501

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
8	5	7	0.8299	0.5833	0.0164	0.0875	0.7314	0.6407	0.6183	0.8436	0.7312
8	5	8	0.3159	0.6597	0.6299	0.1655	0.7563	0.4707	0.2762	0.903	0.756
8	6	7	0.0006	0.9454	0.0528	0.0652	0.31	0.763	0.3971	0.9782	0.3095
8	6	8	0.0081	0.8596	0.9881	0.128	0.3259	0.578	0.7981	0.9615	0.3254
8	7	8	0.4305	0.9137	0.0547	0.7467	0.9738	0.7989	0.5545	0.9398	0.9738
9	1	5	0.5006	0.1189	0.0334	0.9148	0.0336	0.2676	0.3508	0.0196	0.0357
9	1	6	0.9269	0.219	0.119	0.176	0.0447	0.2921	0.9058	0.0055	0.0303
9	1	7	0.6761	0.2201	0.0909	0.802	0.2206	0.1293	0.3996	0.0761	0.2235
9	1	8	0.9711	0.2761	0.201	0.8481	0.1536	0.2267	0.4126	0.1155	0.1557
9	5	6	0.2851	0.5557	0.3024	0.0217	0.793	0.9285	0.1695	0.365	0.8733
9	5	7	0.6365	0.5521	0.4264	0.7913	0.0687	0.4927	0.8778	0.2581	0.0707
9	5	8	0.2419	0.4031	0.1253	0.8766	0.1559	0.8662	0.847	0.1256	0.1631
9	6	7	0.5457	0.9956	0.8114	0.0393	0.1093	0.4394	0.222	0.0447	0.055
9	6	8	0.9181	0.8033	0.6117	0.0299	0.2346	0.7968	0.2371	0.0165	0.1293
9	7	8	0.4796	0.8076	0.4556	0.9118	0.6792	0.6047	0.9688	0.6877	0.6789
10	5	6	0.0063	0.9436	0.9292	0.0806	0.4088	0.8586	0.4596	0.8584	0.7463
10	5	7	0.4443	0.9943	0.9749	0.7689	0.4183	0.5631	0.8457	0.9512	0.7463
10	5	8	0.3026	0.8234	0.7122	0.8105	0.774	0.956	0.9376	0.3796	0.8705
10	6	7	0.0449	0.9485	0.9536	0.1371	0.995	0.6839	0.345	0.8024	0.9924
10	6	8	0.1049	0.8731	0.769	0.1423	0.626	0.8154	0.4149	0.2715	0.6295
10	7	8	0.7637	0.8261	0.7302	0.9653	0.6307	0.5277	0.9087	0.3973	0.632
11	5	6	0.0412	0.6095	0.9427	0.1936	0.9454	0.1611	0.12	0.7544	0.8409
11	5	7	0.0827	0.779	0.9329	0.7347	0.1568	0.7592	0.9894	0.6885	0.1943
11	5	8	0.1543	0.5488	0.9127	0.8852	0.0127	0.8421	0.9534	0.2807	0.018

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
11	6	7	0.8023	0.8194	0.9877	0.0863	0.0993	0.0837	0.1122	0.9079	0.0978
11	6	8	0.5268	0.9201	0.8472	0.1231	0.0041	0.1018	0.1244	0.1221	0.0041
11	7	8	0.7182	0.7468	0.8405	0.8339	0.2766	0.911	0.9419	0.118	0.2792
12	2	3	0.6523	0.6067	0.9781	0.79	0.9856	0.894	0.4701	0.5912	0.9872
12	2	4	0.8781	0.8791	0.9141	0.789	0.8464	0.9031	0.5733	0.0256	0.8524
12	2	5	0.0058	0.0039	0.0781	0.4518	0.4261	0.2674	0.2043	0.6709	0.4303
12	2	6	0.1899	0.001	0.009	0.7821	0.4004	0.4386	0.8124	0.7588	0.4024
12	2	7	0.2992	0.0013	0.0179	0.9756	0.4687	0.2301	0.2524	0.5708	0.4736
12	2	8	0.2628	0.0013	0.0566	0.2061	0.8007	0.2592	0.2493	0.7628	0.8027
12	3	4	0.5911	0.7552	0.8986	0.9763	0.8359	0.9934	0.8966	0.0783	0.8432
12	3	5	0.0409	0.0397	0.1107	0.3085	0.4208	0.2402	0.7421	0.8154	0.4262
12	3	6	0.496	0.0155	0.0175	0.5634	0.3956	0.3861	0.5327	0.7181	0.3991
12	3	7	0.6683	0.0186	0.0316	0.7717	0.4624	0.2083	0.8328	0.9158	0.4687
12	3	8	0.6051	0.0182	0.0836	0.1344	0.7871	0.2332	0.8243	0.7307	0.7909
12	4	5	0.0164	0.0251	0.1159	0.3643	0.6976	0.2576	0.6364	0.0274	0.695
12	4	6	0.2198	0.0103	0.0237	0.5976	0.678	0.4051	0.6595	0.02	0.6735
12	4	7	0.3129	0.0122	0.0391	0.7773	0.7434	0.225	0.7189	0.0337	0.7408
12	4	8	0.2807	0.0119	0.0905	0.1874	0.9817	0.2504	0.7114	0.0229	0.987
12	5	6	0.0403	0.6233	0.2664	0.5015	0.9665	0.6585	0.1756	0.8578	0.9625
12	5	7	0.0162	0.6903	0.4333	0.2768	0.9022	0.9104	0.8668	0.8487	0.9027
12	5	8	0.0294	0.6575	0.8411	0.4877	0.4673	0.9797	0.8807	0.8727	0.471
12	6	7	0.7039	0.9256	0.7388	0.6637	0.8637	0.5767	0.2329	0.7009	0.8601
12	6	8	0.8243	0.9731	0.3692	0.1672	0.4274	0.6403	0.23	0.9941	0.4282
12	7	8	0.887	0.9547	0.5666	0.0739	0.5263	0.9308	0.9868	0.7264	0.5311



## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
13	1	2	0.2398	0.6848	0.7751	0.6593	0.9848	0.6657	0.7121	0.3313	0.9895
13	1	3	0.4551	0.2715	0.9505	0.6709	0.8296	0.9335	0.6867	0.3864	0.8327
13	1	4	0.7261	0.4475	0.9258	0.8861	0.9809	0.791	0.715	0.975	0.9857
13	1	5	0.0393	0.0209	0.3245	0.902	0.7747	0.0834	0.4173	0.6301	0.7804
13	1	6	0.2516	0.0047	0.0481	0.6655	0.0566	0.3589	0.8903	0.414	0.0572
13	1	7	0.9219	0.0111	0.0763	0.8259	0.673	0.2663	0.3389	0.0424	0.8103
13	1	8	0.1776	0.0033	0.041	0.6792	0.2716	0.0523	0.3388	0.6594	0.274
13	2	3	0.8319	0.3852	0.7366	0.9301	0.8245	0.7164	0.9307	0.8632	0.8242
13	2	4	0.3115	0.6648	0.8134	0.715	0.9953	0.8376	0.9962	0.2189	0.9953
13	2	5	0.3117	0.0163	0.096	0.44	0.7338	0.104	0.5988	0.0499	0.7347
13	2	6	0.8555	0.0021	0.0031	0.9479	0.0149	0.5656	0.731	0.0152	0.0148
13	2	7	0.1355	0.0072	0.0078	0.3749	0.6105	0.4086	0.4755	0.0001	0.7744
13	2	8	0.9371	0.0013	0.0024	0.2465	0.1635	0.0577	0.4756	0.4202	0.1631
13	3	4	0.5976	0.5959	0.8751	0.7256	0.8274	0.8534	0.9275	0.3259	0.8272
13	3	5	0.3574	0.4015	0.4064	0.5386	0.9775	0.0775	0.7396	0.1669	0.9767
13	3	6	0.9171	0.1865	0.0819	0.8904	0.2263	0.3763	0.7077	0.0988	0.2256
13	3	7	0.4202	0.2877	0.1196	0.4861	0.9357	0.2737	0.6261	0.0094	0.9559
13	3	8	0.7782	0.1546	0.0716	0.3843	0.5543	0.0463	0.6292	0.5031	0.5537
13	4	5	0.0309	0.0562	0.1626	0.7206	0.7388	0.0629	0.595	0.5662	0.7397
13	4	6	0.3238	0.0099	0.0073	0.7216	0.0152	0.4173	0.7352	0.3117	0.0151
13	4	7	0.7211	0.0277	0.0165	0.6326	0.615	0.2892	0.4722	0.0113	0.7793
13	4	8	0.2123	0.0066	0.0056	0.4607	0.1656	0.0329	0.4722	0.5391	0.1651
13	5	6	0.148	0.4342	0.1265	0.3898	0.0134	0.1974	0.2899	0.6136	0.0133
13	5	7	0.0033	0.7137	0.2268	0.8827	0.8361	0.3415	0.8171	0.0213	0.96

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
13	5	8	0.2563	0.3419	0.1025	0.655	0.2154	0.7486	0.8239	0.1548	0.2142
13	6	7	0.1118	0.6889	0.7822	0.3199	0.0299	0.7521	0.2015	0.0595	0.015
13	6	8	0.7492	0.8637	0.9147	0.1805	0.2006	0.1047	0.1956	0.0467	0.2002
13	7	8	0.058	0.5706	0.704	0.7738	0.3265	0.2022	0.9887	0.0002	0.2129
14	2	3	0.5554	0.7266	0.4607	0.8524	0.6704	0.8474	0.4714	0.5072	0.6698
14	2	5	0.5697	0.2522	0.3997	0.9616	0.6412	0.239	0.3153	0.1736	0.6408
14	2	6	0.2728	0.0336	0.1005	0.7102	0.7137	0.3147	0.1899	0.2014	0.7135
14	2	7	0.0627	0.1139	0.1647	0.2153	0.3317	0.1584	0.6562	0.0336	0.3263
14	2	8	0.3058	0.028	0.0709	0.6283	0.6069	0.0558	0.5758	0.6242	0.6066
14	3	5	0.853	0.5548	0.9109	0.8065	0.9172	0.1936	0.9243	0.0734	0.9168
14	3	6	0.8032	0.1524	0.574	0.9223	0.8563	0.2536	0.7096	0.0844	0.8558
14	3	7	0.3718	0.3315	0.7187	0.4163	0.7627	0.13	0.6856	0.0168	0.7568
14	3	8	0.8496	0.1356	0.4837	0.8498	0.9472	0.0482	0.7589	0.2668	0.9468
14	5	6	0.5175	0.2289	0.3264	0.6072	0.9033	0.8328	0.7068	0.9186	0.9032
14	5	7	0.1133	0.5844	0.4968	0.1181	0.5325	0.769	0.5007	0.3347	0.5242
14	5	8	0.5765	0.1966	0.237	0.5144	0.9527	0.3669	0.5858	0.2857	0.9527
14	6	7	0.3414	0.5235	0.7763	0.2884	0.4583	0.6151	0.296	0.2875	0.4506
14	6	8	0.9292	0.9297	0.8404	0.8903	0.8565	0.2656	0.3571	0.3343	0.8564
14	7	8	0.2992	0.4686	0.6299	0.3539	0.5708	0.548	0.8929	0.046	0.5623
15	1	2	0.0434	0.9756	0.9849	0.3923	0.9461	0.7844	0.1644	0.5788	0.9508
15	1	3	0.0521	0.0413	0.1274	0.2886	0.9643	0.6788	0.3196	0.7546	0.9822
15	1	4	0.1563	0.1113	0.2101	0.7638	0.9571	0.8928	0.2099	0.4358	0.9536
15	1	5	0.0366	0.1937	0.3912	0.4022	0.9818	0.1601	0.3828	0.0835	0.9884
15	1	6	0.1015	0.0237	0.0834	0.2226	0.9528	0.7322	0.6015	0.2482	0.958

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
15	1	7	0.216	0.0655	0.1587	0.781	0.798	0.2747	0.2298	0.0158	0.7927
15	1	8	0.1043	0.0224	0.0681	0.5304	0.949	0.123	0.3552	0.0955	0.9437
15	2	3	0.9874	0.0149	0.0621	0.7772	0.9813	0.8606	0.6534	0.7966	0.9654
15	2	4	0.5228	0.059	0.1246	0.1762	0.8877	0.6225	0.8894	0.7628	0.8888
15	2	5	0.8937	0.1034	0.2585	0.9066	0.9486	0.1545	0.4054	0.1467	0.9467
15	2	6	0.4564	0.0041	0.0236	0.7142	0.9847	0.9563	0.1965	0.4792	0.9846
15	2	7	0.2067	0.0197	0.0646	0.1164	0.6697	0.3066	0.6773	0.0195	0.6694
15	2	8	0.4463	0.0037	0.0172	0.6888	0.8584	0.109	0.4396	0.1703	0.8582
15	3	4	0.5506	0.6043	0.7577	0.1188	0.912	0.5129	0.7615	0.5999	0.9281
15	3	5	0.914	0.2288	0.3003	0.6691	0.9738	0.237	0.7707	0.1077	0.9898
15	3	6	0.4957	0.9746	0.9839	0.9832	0.9928	0.8822	0.464	0.3506	0.9749
15	3	7	0.243	0.5806	0.7075	0.0736	0.7182	0.4287	0.9103	0.0159	0.7354
15	3	8	0.4858	0.9958	0.8928	0.4864	0.8922	0.1753	0.8169	0.1246	0.9101
15	4	5	0.5534	0.555	0.5045	0.1595	0.922	0.0513	0.5171	0.3226	0.925
15	4	6	0.9745	0.5629	0.7007	0.0611	0.8871	0.5364	0.2747	0.7625	0.8884
15	4	7	0.652	0.9508	0.9936	0.9386	0.8203	0.1186	0.8074	0.0743	0.8187
15	4	8	0.987	0.5452	0.6185	0.2448	0.9982	0.0336	0.5555	0.3651	0.9967
15	5	6	0.4643	0.1351	0.1756	0.5606	0.9559	0.0943	0.5797	0.3573	0.9536
15	5	7	0.1758	0.4028	0.3939	0.0818	0.669	0.6194	0.6095	0.3077	0.6707
15	5	8	0.452	0.1266	0.1337	0.7356	0.8939	0.8329	0.9385	0.8953	0.896
15	6	7	0.5254	0.5044	0.6096	0.0179	0.6179	0.2361	0.2834	0.0457	0.6175
15	6	8	0.9835	0.9728	0.8824	0.3478	0.8454	0.0581	0.5249	0.4158	0.8453
15	7	8	0.5389	0.4829	0.5102	0.1518	0.7612	0.4764	0.662	0.2351	0.761
16	1	2	0.0355	0.8781	0.9602	0.4766	0.9697	0.7284	0.2377	0.6444	0.9744

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
16	1	3	0.287	0.3096	0.4107	0.6145	0.9815	0.8074	0.4687	0.6648	0.9767
16	1	4	0.1642	0.5024	0.2926	0.9039	0.9679	0.8653	0.2625	0.9473	0.9726
16	1	5	0.0567	0.1221	0.1499	0.4137	0.9548	0.0902	0.2279	0.3882	0.96
16	1	6	0.0826	0.1198	0.0819	0.4206	0.903	0.1763	0.5331	0.1096	0.9081
16	1	7	0.1127	0.2475	0.1709	0.5571	0.8777	0.1437	0.1475	0.0628	0.8724
16	1	8	0.0908	0.0892	0.0696	0.7539	0.9646	0.0941	0.2608	0.4983	0.9698
16	2	3	0.2021	0.2908	0.3434	0.7985	0.9403	0.8995	0.5767	0.9725	0.9402
16	2	4	0.3815	0.5263	0.2191	0.4684	0.9978	0.8283	0.9411	0.6278	0.9978
16	2	5	0.6064	0.0753	0.0735	0.9608	0.9845	0.0907	0.9094	0.0772	0.9845
16	2	6	0.4621	0.0733	0.0295	0.9732	0.9174	0.211	0.3873	0.0066	0.9173
16	2	7	0.3528	0.202	0.0893	0.8034	0.8005	0.1638	0.8419	0.0023	0.8003
16	2	8	0.4279	0.0481	0.023	0.5467	0.9971	0.0959	0.827	0.1265	0.9971
16	3	4	0.6885	0.6722	0.778	0.6385	0.938	0.9279	0.6281	0.6524	0.938
16	3	5	0.338	0.5752	0.4855	0.7308	0.9156	0.0662	0.5955	0.0841	0.9155
16	3	6	0.4605	0.567	0.2774	0.7426	0.8492	0.1626	0.8258	0.0074	0.849
16	3	7	0.5863	0.9551	0.5443	0.9634	0.8681	0.124	0.3987	0.0026	0.8679
16	3	8	0.4961	0.4479	0.2368	0.7581	0.9282	0.0702	0.6701	0.1367	0.9281
16	4	5	0.6202	0.2943	0.7099	0.3755	0.9871	0.0523	0.9773	0.2266	0.987
16	4	6	0.7831	0.2888	0.4467	0.3839	0.92	0.1335	0.4358	0.0308	0.9199
16	4	7	0.9352	0.5858	0.7788	0.5563	0.798	0.1005	0.7758	0.0125	0.7978
16	4	8	0.8276	0.2124	0.391	0.8146	0.9997	0.0555	0.894	0.3325	0.9997
16	5	6	0.7873	0.9882	0.6337	0.9847	0.9178	0.5885	0.3579	0.2425	0.9178
16	5	7	0.6119	0.537	0.9111	0.7151	0.7389	0.7135	0.7013	0.1135	0.7387
16	5	8	0.7337	0.8079	0.5517	0.4247	0.9845	0.9742	0.8979	0.7685	0.9845

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
16	6	7	0.8122	0.5273	0.5564	0.7294	0.6626	0.8618	0.1928	0.678	0.7534
16	6	8	0.9439	0.8194	0.9055	0.4359	0.9024	0.6109	0.4288	0.1436	0.8724
16	7	8	0.8673	0.3896	0.4796	0.6647	0.7537	0.7378	0.6087	0.0607	0.9835
17	2	3	0.476	0.793	0.7823	0.8691	0.8641	0.932	0.753	0.732	0.9695
17	2	4	0.2062	0.9652	0.5099	0.5595	0.9835	0.7337	0.8942	0.9574	0.9048
17	2	5	0.5943	0.6895	0.682	0.9732	0.9595	0.0981	0.8768	0.5306	0.9126
17	2	6	0.6642	0.2013	0.1998	0.7213	0.8965	0.3371	0.5278	0.4761	0.9427
17	2	7	0.2453	0.138	0.1681	0.8842	0.9243	0.3431	0.9237	0.0681	0.8887
17	2	8	0.4176	0.6569	0.5532	0.649	0.9327	0.1616	0.7362	0.6367	0.8658
17	3	4	0.5818	0.8268	0.7024	0.676	0.8804	0.6712	0.8555	0.6923	0.9277
17	3	5	0.704	0.9471	0.9544	0.8589	0.865	0.123	0.8123	0.2804	0.7489
17	3	6	0.6234	0.3473	0.355	0.5681	0.9251	0.3955	0.8154	0.2526	0.8923
17	3	7	0.8126	0.2521	0.3071	0.7189	0.7496	0.402	0.6233	0.0231	0.9908
17	3	8	0.9174	0.9123	0.8106	0.8078	0.8915	0.1975	0.9546	0.3611	0.9263
17	4	5	0.2779	0.7306	0.6673	0.4753	0.9808	0.0381	0.9915	0.5777	0.8912
17	4	6	0.2279	0.2217	0.6656	0.2652	0.9179	0.1663	0.6424	0.5188	0.964
17	4	7	0.6327	0.1534	0.597	0.3665	0.9029	0.1699	0.7924	0.0793	0.8857
17	4	8	0.4178	0.6974	0.8039	0.7691	0.954	0.0686	0.8643	0.6866	0.7915
17	5	6	0.8568	0.1531	0.1479	0.5022	0.8888	0.2955	0.4713	0.8438	0.9536
17	5	7	0.2883	0.0777	0.1079	0.7576	0.7942	0.2877	0.7019	0.0205	0.6686
17	5	8	0.6436	0.9439	0.7651	0.4788	0.9536	0.7062	0.7852	0.7939	0.9337
17	6	7	0.1953	0.7275	0.867	0.705	0.6744	0.986	0.2589	0.0682	0.7449
17	6	8	0.5078	0.1725	0.2517	0.1584	0.9369	0.5052	0.6564	0.6783	0.9704
17	7	8	0.5573	0.0888	0.1909	0.2952	0.7476	0.4943	0.5072	0.0168	0.9234

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
18	1	5	0.4898	0.1781	0.224	0.7399	0.9655	0.0736	0.2362	0.7051	0.932
18	1	6	0.3433	0.4882	0.3167	0.6882	0.9125	0.156	0.6041	0.8457	0.9618
18	1	7	0.4727	0.4861	0.2687	0.73	0.943	0.2993	0.2743	0.4503	0.9297
18	1	8	0.2147	0.5356	0.3536	0.5777	0.9527	0.0498	0.4621	0.8131	0.8432
18	5	6	0.729	0.2249	0.6324	0.9393	0.921	0.4757	0.2373	0.7351	0.9894
18	5	7	0.9755	0.227	0.7609	0.9873	0.852	0.1807	0.8172	0.4935	0.6998
18	5	8	0.4097	0.2128	0.5929	0.7404	0.9834	0.8298	0.4392	0.804	0.9303
18	6	7	0.6323	0.9946	0.8295	0.9063	0.7001	0.4854	0.2791	0.2729	0.8014
18	6	8	0.5409	0.9092	0.9202	0.7486	0.9275	0.3177	0.6833	0.936	0.9668
18	7	8	0.296	0.9043	0.766	0.6695	0.8043	0.0956	0.5348	0.3377	0.934
19	4	5	0.4541	0.6166	0.7726	0.4976	0.9669	0.0175	0.5143	0.5888	0.8776
19	4	6	0.9793	0.8378	0.7333	0.5744	0.9335	0.1376	0.9144	0.2628	0.8876
19	4	7	0.5198	0.8811	0.9395	0.4705	0.885	0.3318	0.6168	0.3933	0.9625
19	4	8	0.3578	0.9666	0.81	0.2874	0.8848	0.0666	0.8613	0.8775	0.8873
19	5	6	0.2305	0.6207	0.9833	0.7768	0.9615	0.1262	0.2567	0.4027	0.9005
19	5	7	0.7883	0.5738	0.734	0.9561	0.8969	0.0279	0.7673	0.6696	0.8885
19	5	8	0.9107	0.4818	0.9116	0.6791	0.8966	0.3145	0.4656	0.5177	0.9078
19	6	7	0.1897	0.9176	0.6095	0.7465	0.9041	0.3863	0.2808	0.6148	0.9814
19	6	8	0.0667	0.761	0.8533	0.3215	0.9035	0.5355	0.6223	0.0701	0.9809
19	7	8	0.5994	0.843	0.7573	0.5145	0.9994	0.147	0.5779	0.1899	0.9816
20	1	2	0.0174	0.9312	0.9114	0.9753	0.9779	0.9263	0.9996	0.6764	0.7684
20	1	3	0.0001	0.7879	0.671	0.9896	0.9852	0.9017	0.934	0.5757	0.3398
20	1	4	0.0025	0.9581	0.9677	0.8179	0.7731	0.9092	0.818	0.854	0.2846
20	1	5	<.0001	0.4847	0.5513	0.4994	0.3392	0.1898	0.0415	0.7369	0.2449

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
20	1	6	<.0001	0.1953	0.1802	0.4485	0.288	0.1509	0.5785	0.3902	0.1704
20	1	7	<.0001	0.2586	0.2461	0.7843	0.2418	0.1159	0.0818	0.3743	0.9581
20	1	8	<.0001	0.0658	0.0987	0.3567	0.1694	0.0158	0.144	0.7448	0.7169
20	2	3	0.1036	0.6928	0.7271	0.9609	0.9587	0.8114	0.9274	0.8742	0.2739
20	2	4	0.5529	0.8724	0.8593	0.7662	0.7187	0.9833	0.798	0.7711	0.1998
20	2	5	0.0262	0.4953	0.4294	0.4298	0.2715	0.1164	0.0231	0.3994	0.1867
20	2	6	0.0893	0.1665	0.0884	0.3552	0.2011	0.0781	0.5246	0.1173	0.1204
20	2	7	0.0064	0.2347	0.1374	0.7201	0.1855	0.0561	0.0469	0.1131	0.7593
20	2	8	0.0117	0.0457	0.0414	0.2702	0.1207	0.0043	0.096	0.3598	0.2976
20	3	4	0.2537	0.7968	0.5837	0.8063	0.7605	0.7883	0.872	0.6454	0.2229
20	3	5	0.5557	0.2784	0.2529	0.459	0.2947	0.1868	0.0293	0.3169	0.1669
20	3	6	0.7957	0.0633	0.0338	0.3865	0.224	0.1382	0.5969	0.079	0.1066
20	3	7	0.4163	0.0981	0.0578	0.7638	0.166	0.1021	0.0596	0.0765	0.4196
20	3	8	0.5191	0.0141	0.0146	0.2953	0.1071	0.0096	0.0764	0.272	0.334
20	4	5	0.0761	0.3752	0.5088	0.5871	0.4148	0.0971	0.0345	0.542	0.0581
20	4	6	0.2577	0.0889	0.1003	0.5168	0.3345	0.0598	0.7135	0.1706	0.0333
20	4	7	0.0232	0.1385	0.1602	0.9748	0.058	0.0418	0.0709	0.164	0.97
20	4	8	0.0406	0.0189	0.045	0.3943	0.0336	0.0025	0.0391	0.5099	0.0092
20	5	6	0.3317	0.5517	0.4361	0.9826	0.9617	0.9944	0.038	0.5822	0.005
20	5	7	0.9029	0.6827	0.5662	0.5667	0.0089	0.8476	0.5518	0.5569	0.0006
20	5	8	0.9743	0.2097	0.2475	0.8447	0.0049	0.2139	<.0001	0.9538	0.0003
20	6	7	0.1576	0.8217	0.8044	0.466	0.0006	0.8265	0.0791	0.9485	0.7367
20	6	8	0.2444	0.3871	0.6008	0.7782	0.0003	0.1458	0.0036	0.4433	0.916
20	7	8	0.8488	0.292	0.4588	0.3403	0.7414	0.2239	<.0001	0.4215	0.514

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
21	1	2	0.0732	0.9975	0.5896	0.8013	0.9111	0.8594	0.7088	0.8508	0.8323
21	1	3	0.0145	0.8914	0.2747	0.3425	0.5152	0.6879	0.5765	0.7529	0.1283
21	1	4	0.0164	0.3494	0.8933	0.2307	0.8334	0.1994	0.5614	0.9919	0.9076
21	1	5	<.0001	0.0657	0.5107	0.4955	0.1286	0.0214	0.0008	0.2193	0.7344
21	1	6	<.0001	0.0012	0.0662	0.0997	0.9045	0.0302	0.031	0.0381	0.4778
21	1	7	<.0001	0.0003	0.0425	0.8062	0.7376	0.0404	0.0006	0.044	0.4437
21	1	8	<.0001	0.0039	0.2716	0.5857	0.4791	0.0019	0.0246	0.2942	0.7454
21	2	3	0.5677	0.8853	0.5877	0.2175	0.441	0.8157	0.8535	0.909	0.1003
21	2	4	0.5994	0.3328	0.4738	0.1373	0.7415	0.2449	0.8352	0.8485	0.993
21	2	5	0.0038	0.0556	0.1892	0.3235	0.0992	0.0248	0.0018	0.3108	0.6421
21	2	6	0.0099	0.0007	0.011	0.048	0.9904	0.0355	0.066	0.063	0.556
21	2	7	0.0026	0.0002	0.0062	0.9598	0.64	0.048	0.0013	0.072	0.6338
21	2	8	0.0229	0.0027	0.0768	0.3956	0.5622	0.0019	0.0527	0.404	0.3709
21	3	4	0.9609	0.388	0.1852	0.7873	0.6341	0.3414	0.9809	0.742	0.3559
21	3	5	0.0145	0.0632	0.0422	0.6999	0.3705	0.0411	0.0025	0.3302	0.6731
21	3	6	0.036	0.0007	0.0008	0.5131	0.3548	0.0582	0.091	0.057	0.1212
21	3	7	0.0105	0.0002	0.0004	0.1522	0.6713	0.0776	0.0018	0.0662	0.1567
21	3	8	0.0756	0.0026	0.0118	0.5913	0.1223	0.0035	0.0729	0.4368	0.6995
21	4	5	0.0125	0.3695	0.5744	0.4944	0.1567	0.3332	0.0028	0.1822	0.9079
21	4	6	0.0314	0.0149	0.0626	0.7276	0.6976	0.4209	0.0963	0.0231	0.3037
21	4	7	0.0089	0.0049	0.0382	0.0825	0.9104	0.4984	0.002	0.0273	0.0379
21	4	8	0.0671	0.0403	0.295	0.4035	0.3055	0.0644	0.0773	0.255	0.1303
21	5	6	0.6377	0.0782	0.1382	0.2314	0.0376	0.8348	0.1025	0.3084	0.0064
21	5	7	0.9479	0.028	0.0843	0.237	0.1294	0.7205	0.9418	0.3451	0.5562



## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
21	5	8	0.4431	0.185	0.5799	0.8644	0.0064	0.2987	0.1428	0.8259	0.4479
21	6	7	0.5791	0.6479	0.7982	0.0139	0.5566	0.8787	0.082	0.9382	0.1856
21	6	8	0.7486	0.6837	0.3578	0.1687	0.4524	0.2047	0.8838	0.2125	0.406
21	7	8	0.3914	0.3944	0.2437	0.3127	0.1883	0.157	0.1172	0.2412	0.7068
22	1	2	0.0126	0.7885	0.8115	0.0561	0.4072	0.7906	0.6793	0.6683	0.2959
22	1	3	<.0001	0.9497	0.6927	0.0648	0.7063	0.8615	0.3586	0.6268	0.2935
22	1	4	0.0156	0.8826	0.5703	0.1264	0.297	0.6466	0.783	0.5424	0.4715
22	1	5	<.0001	0.0352	0.0795	0.2556	0.2946	0.0078	0.0014	0.9144	0.4086
22	1	6	<.0001	0.0056	0.0147	0.0561	0.4728	0.0106	0.0598	0.2552	0.4687
22	1	7	<.0001	0.0004	0.0021	0.5374	0.4098	0.0159	0.0003	0.1229	0.1924
22	1	8	<.0001	0.0024	0.0139	0.0721	0.4699	0.0018	0.001	0.2283	0.8167
22	2	3	0.0959	0.8246	0.4936	0.9449	0.1928	0.9218	0.5861	0.9502	0.9002
22	2	4	0.9326	0.8963	0.7221	0.6788	0.8169	0.8354	0.8817	0.8451	0.81
22	2	5	0.0185	0.0461	0.1005	0.2592	0.9003	0.0093	0.0026	0.5135	0.9024
22	2	6	0.0477	0.0063	0.0163	0.7863	0.8102	0.0129	0.1181	0.0732	0.814
22	2	7	0.0113	0.0003	0.0019	0.0886	0.9025	0.0199	0.0004	0.0252	0.1248
22	2	8	0.0235	0.0026	0.0153	0.6929	0.8142	0.0019	0.0018	0.0621	0.1031
22	3	4	0.0802	0.9273	0.2983	0.7301	0.1252	0.7596	0.4882	0.8943	0.2058
22	3	5	0.6635	0.0245	0.0151	0.2943	0.1034	0.0066	0.0171	0.4681	0.1668
22	3	6	0.954	0.0028	0.0014	0.8482	0.2063	0.0093	0.3496	0.0624	0.204
22	3	7	0.5396	0.0001	0.0001	0.1045	0.1672	0.0147	0.0037	0.0209	0.8869
22	3	8	0.7309	0.0011	0.0013	0.7526	0.2045	0.0013	0.0125	0.0527	0.6115
22	4	5	0.0142	0.032	0.2177	0.5153	0.887	0.0181	0.0015	0.3794	0.6963
22	4	6	0.0378	0.004	0.0461	0.836	0.6118	0.0246	0.0829	0.0438	0.6151

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N	p-values
22	4	7	0.0086	0.0002	0.0069	0.2202	0.6966	0.0367	0.0002	0.0138	0.6541	
22	4	8	0.0182	0.0015	0.0438	0.9337	0.6154	0.0042	0.001	0.0366	0.7612	
22	5	6	0.644	0.3647	0.3499	0.2937	0.6545	0.8867	0.0751	0.1628	0.6587	
22	5	7	0.8271	0.0505	0.071	0.4807	0.7615	0.7353	0.5265	0.0519	0.8853	
22	5	8	0.9112	0.2076	0.3361	0.3688	0.659	0.5373	0.8903	0.1371	0.995	
22	6	7	0.4961	0.2929	0.3832	0.0795	0.8855	0.845	0.016	0.5824	0.8903	
22	6	8	0.7259	0.7232	0.9784	0.8795	0.995	0.4477	0.0552	0.9274	0.8478	
22	7	8	0.7414	0.4852	0.3981	0.109	0.8904	0.3398	0.6203	0.6463	0.876	
23	5	6	0.338	0.4649	0.4641	0.1942	0.8471	0.5256	0.1605	0.5041	0.9325	
23	5	7	0.3894	0.7004	0.8211	0.4542	0.873	0.2317	0.3492	0.8273	0.9632	
23	5	8	0.6357	0.717	0.7123	0.1267	0.9314	0.3325	0.6565	0.446	0.8963	
23	6	7	0.9015	0.6782	0.5384	0.4915	0.9661	0.5374	0.0085	0.5637	0.9315	
23	6	8	0.5673	0.2007	0.1912	0.7558	0.8969	0.709	0.2887	0.8899	0.9301	
23	7	8	0.6499	0.3792	0.4764	0.3267	0.9293	0.813	0.1235	0.4874	0.8787	
24	4	5	0.9512	0.7852	0.7421	0.711	0.9195	0.3573	0.033	0.6912	0.7095	
24	4	6	0.9891	0.8572	0.9804	0.8623	0.8732	0.0001	0.5381	0.2874	0.7899	
24	4	7	0.8005	0.7542	0.5756	0.1377	0.706	0.0743	0.0171	0.1894	0.985	
24	4	8	0.8287	0.6966	0.8505	0.3719	0.7863	0.0028	0.2418	0.4274	0.8573	
24	5	6	0.9355	0.6385	0.6906	0.7789	0.9927	0.0072	0.0547	0.2053	0.9204	
24	5	7	0.783	0.9575	0.9356	0.4502	0.8666	0.5277	0.7571	0.1469	0.77	
24	5	8	0.8056	0.5123	0.5872	0.777	0.9297	0.0695	0.1482	0.2901	0.8832	
24	6	7	0.7416	0.4936	0.4198	0.0714	0.7726	0.0041	0.0187	0.7803	0.8734	
24	6	8	0.7802	0.7791	0.8224	0.325	0.8859	0.2115	0.4685	0.6645	0.9778	
24	7	8	0.9576	0.3058	0.2709	0.3786	0.8735	0.0945	0.0915	0.4354	0.5948	

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
25	3	4	0.8078	0.1207	0.1565	0.5984	0.971	0.467	0.3642	0.4638	0.9079
25	3	5	0.4672	0.0175	0.0214	0.5814	0.5912	0.0158	0.0328	0.2225	0.8759
25	3	6	0.9853	0.0088	0.0075	0.7423	0.9033	0.084	0.7561	0.5792	0.9214
25	3	7	0.6266	0.1449	0.1838	0.4973	0.8763	0.2544	0.1919	0.8007	0.5079
25	3	8	0.4722	0.076	0.076	0.9413	0.9188	0.0079	0.1711	0.5065	0.9118
25	4	5	0.5487	0.4037	0.3514	0.1275	0.5118	0.0386	0.1436	0.0068	0.8728
25	4	6	0.7026	0.2385	0.1488	0.2279	0.9157	0.2378	0.3619	0.0721	0.9297
25	4	7	0.772	0.8001	0.8175	0.1157	0.8823	0.6555	0.6759	0.1925	0.4594
25	4	8	0.5567	0.9238	0.7719	0.5133	0.9361	0.0177	0.6316	0.058	0.5769
25	5	6	0.1825	0.6207	0.4635	0.6969	0.4602	0.2561	0.0017	0.2406	0.4722
25	5	7	0.7472	0.1913	0.1657	0.7906	0.571	0.0556	0.2264	0.1463	0.9417
25	5	8	0.9778	0.3514	0.4271	0.2916	0.4703	0.6199	0.2223	0.3739	0.9805
25	6	7	0.4221	0.0911	0.0499	0.5606	0.9491	0.3954	0.1087	0.6644	0.9271
25	6	8	0.2163	0.1759	0.1515	0.5067	0.9773	0.1207	0.0793	0.839	0.6596
25	7	8	0.7467	0.6776	0.5417	0.2531	0.9314	0.0235	0.9561	0.5527	0.683
26	5	6	0.3339	0.6037	0.427	0.0874	0.6555	0.5602	0.0041	0.8242	0.4836
26	5	7	0.6829	0.1893	0.1665	0.8834	0.6782	0.146	0.041	0.5913	0.8105
26	5	8	0.8169	0.9021	0.8759	0.3054	0.483	0.9093	0.0258	0.9884	0.9952
26	6	7	0.5308	0.1402	0.0772	0.1272	0.8761	0.5169	0.2879	0.5662	0.7185
26	6	8	0.4265	0.6754	0.5031	0.3194	1	0.6357	0.2984	0.8172	0.9167
26	7	8	0.8494	0.1673	0.1376	0.4317	0.8149	0.1951	0.9453	0.6023	0.4481
27	1	2	0.0322	0.622	0.6845	0.4815	0.9942	0.8001	0.5796	0.6845	0.6042
27	1	3	0.0151	0.9898	0.6871	0.5953	0.7205	0.54	0.3044	0.3323	0.7266
27	1	4	0.056	0.8629	0.6405	0.9725	0.9105	0.6585	0.652	0.8654	0.826

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
27	1	5	0.0005	0.2487	0.4813	0.2267	0.4461	0.089	0.0027	0.8118	0.723
27	1	6	0.0142	0.1127	0.2344	0.5643	0.6047	0.2849	0.2053	0.6242	0.9221
27	1	7	0.0029	0.7294	0.8769	0.1287	0.7263	0.252	0.234	0.8266	0.4525
27	1	8	0.002	0.1221	0.21	0.6919	0.8235	0.0331	0.0962	0.9664	0.6102
27	2	3	0.7718	0.613	0.9971	0.8627	0.7259	0.3857	0.6358	0.5733	0.7321
27	2	4	0.5375	0.679	0.9883	0.387	0.9171	0.8903	0.8298	0.7617	0.8318
27	2	5	0.4994	0.0719	0.2161	0.7722	0.4515	0.0413	0.0225	0.444	0.7542
27	2	6	0.8118	0.0271	0.0892	0.7591	0.6118	0.1623	0.5787	0.3227	0.7701
27	2	7	0.7702	0.3319	0.7202	0.5229	0.733	0.1397	0.6315	0.7775	0.9407
27	2	8	0.7201	0.0294	0.076	0.6137	0.8306	0.0138	0.3426	0.5766	0.9254
27	3	4	0.338	0.8509	0.9917	0.5091	0.7625	0.2363	0.4329	0.3385	0.8124
27	3	5	0.7672	0.2557	0.218	0.6062	0.765	0.37	0.0969	0.1352	0.3962
27	3	6	0.5467	0.1164	0.0897	0.9281	0.9387	0.7798	0.9572	0.092	0.6042
27	3	7	0.9429	0.7416	0.7238	0.3926	0.9281	0.7214	0.8972	0.3284	0.7608
27	3	8	0.9896	0.126	0.0765	0.7766	0.8174	0.1792	0.7367	0.2023	0.8907
27	4	5	0.0599	0.0559	0.0856	0.0853	0.4002	0.0013	0.0002	0.5693	0.7453
27	4	6	0.5762	0.0148	0.0219	0.4151	0.6123	0.0264	0.2628	0.3907	0.553
27	4	7	0.2055	0.4661	0.6414	0.0386	0.7686	0.0197	0.3121	0.9601	0.3788
27	4	8	0.1623	0.0158	0.0152	0.5565	0.8963	0.0002	0.09	0.7654	0.81
27	5	6	0.1324	0.4059	0.3765	0.3244	0.7406	0.2697	0.0022	0.6726	0.6426
27	5	7	0.5473	0.1787	0.1504	0.5433	0.55	0.3368	0.0014	0.473	0.8353
27	5	8	0.5927	0.4496	0.3112	0.1663	0.3787	0.3869	0.0159	0.746	0.8907
27	6	7	0.4171	0.0478	0.0354	0.1513	0.8112	0.894	0.898	0.3068	0.7453
27	6	8	0.3427	0.9198	0.9403	0.7643	0.6467	0.0647	0.5022	0.4911	0.553

## Appendix G. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
27	7	8	0.9247	0.0513	0.0236	0.071	0.8386	0.0872	0.4236	0.6895	0.8149
28	1	2	0.0292	0.5939	0.9707	0.5228	0.8157	0.7853	0.9887	0.5111	0.8916
28	1	3	0.0039	0.5382	0.6045	0.6215	0.8885	0.6798	0.2085	0.8451	0.8422
28	1	4	0.0067	0.6522	0.5646	0.4213	0.8424	0.8466	0.5647	0.6781	0.2563
28	1	5	<.0001	0.0117	0.2958	0.8119	0.2587	<.0001	0.0015	0.8253	0.2563
28	1	6	<.0001	<.0001	0.0228	0.1764	0.5306	<.0001	0.0288	0.074	0.5269
28	1	7	<.0001	0.009	0.1673	0.1128	0.8039	0.0084	0.0198	0.2185	0.804
28	1	8	<.0001	0.0007	0.059	0.097	0.4129	<.0001	0.0581	0.6785	0.4096
28	2	3	0.347	0.8897	0.5813	0.9384	0.9456	0.5098	0.2036	0.6947	0.9418
28	2	4	0.5958	0.9341	0.5405	0.8699	0.9725	0.6407	0.5744	0.8083	0.9719
28	2	5	0.0034	0.0589	0.3165	0.6009	0.3934	<.0001	0.0014	0.3175	0.3909
28	2	6	0.0242	0.001	0.0254	0.0366	0.7202	<.0001	0.0275	0.011	0.7168
28	2	7	0.0118	0.0463	0.1808	0.02	0.9831	0.0031	0.0189	0.0466	0.9821
28	2	8	0.0281	0.0052	0.0646	0.0172	0.5764	<.0001	0.0558	0.2492	0.5732
28	3	4	0.6417	0.8316	0.9969	0.8231	0.9702	0.8094	0.0759	0.8611	0.9669
28	3	5	0.1485	0.1433	0.1362	0.7183	0.417	0.002	0.1968	0.6799	0.4117
28	3	6	0.3669	0.0068	0.0108	0.0851	0.6993	0.0021	0.6266	0.0776	0.6925
28	3	7	0.2611	0.1173	0.0758	0.0541	0.9537	0.0688	0.5523	0.1989	0.9504
28	3	8	0.3793	0.0227	0.0269	0.0469	0.5744	0.0006	0.8008	0.5649	0.5681
28	4	5	0.0214	0.0468	0.0834	0.4726	0.3712	<.0001	0.0001	0.4763	0.3683
28	4	6	0.1005	0.0007	0.0033	0.0228	0.6908	0.0001	0.0043	0.0237	0.6868
28	4	7	0.0569	0.0366	0.0404	0.0119	0.9851	0.0154	0.0026	0.0875	0.9855
28	4	8	0.1103	0.0039	0.0112	0.0104	0.5508	<.0001	0.0105	0.3795	0.5471
28	5	6	0.4481	0.0557	0.1026	0.0423	0.546	0.9473	0.2461	0.045	0.546

**Appendix G. Continued.**

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	DO	Org-N
			p-values								
28	5	7	0.6569	0.8485	0.6409	0.0192	0.2766	0.0603	0.3048	0.1949	0.2733
28	5	8	0.4567	0.2014	0.2536	0.0171	0.7559	0.5298	0.1407	0.7963	0.7562
28	6	7	0.7579	0.0955	0.2574	0.7818	0.6417	0.0642	0.8816	0.4913	0.6366
28	6	8	0.9906	0.5784	0.6739	0.6803	0.7987	0.5903	0.7462	0.1102	0.7985
28	7	8	0.7566	0.2892	0.5004	0.8824	0.4841	0.0182	0.6348	0.3459	0.4797

**Appendix H. Differences of least squares means in time series analysis for N and P forms, pH, and EC for each sampling event throughout the study (September 2006-December 2008).**

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	Org-N	p-values	
3	5	6	0.9182	0.3335	0.3755	0.4488	0.9618	0.7846	0.7384	0.9618		
3	5	7	0.0517	0.7141	0.836	0.8803	0.807	0.5526	0.4042	0.807		
3	5	8	0.4541	0.3224	0.8016	0.8631	0.9798	0.9036	0.151	0.9798		
3	6	7	0.1484	0.2137	0.4386	0.3773	0.9069	0.902	0.8177	0.9069		
3	6	8	0.6436	0.8591	0.5154	0.3988	0.9489	0.8665	0.4438	0.9489		
3	7	8	0.0132	0.1742	0.9344	0.961	0.809	0.6921	0.4346	0.809		
4	6	7	0.7554	0.2398	0.1536	0.716	0.9361	0.598	0.4729	0.9361		
4	6	8	0.9809	0.6279	0.4171	0.3561	1	0.5792	0.6832	1		
4	7	8	0.7266	0.5551	0.6562	0.4461	0.9361	0.8903	0.2123	0.9361		
5	5	6	0.6157	0.0734	0.0169	0.3499	0.9044	0.0999	0.0724	0.9044		
5	5	7	0.2949	0.5919	0.969	0.9658	0.9833	0.5243	0.8364	0.9833		
5	5	8	0.5957	0.4013	0.3493	0.777	0.9339	0.5819	0.3146	0.9339		
5	6	7	0.1432	0.0461	0.0448	0.4567	0.9051	0.4415	0.1766	0.9051		
5	6	8	0.9876	0.2578	0.0873	0.4625	0.8303	0.2136	0.3408	0.8303		
5	7	8	0.1239	0.2177	0.4329	0.8521	0.9653	0.8258	0.5276	0.9653		
6	5	6	0.3051	0.7914	0.5537	0.3927	0.8257	0.5349	0.5042	0.8257		
6	5	7	0.8969	0.3011	0.2529	0.8532	0.9897	0.1304	0.3994	0.9897		
6	5	8	0.8411	0.1431	0.1403	0.7293	0.7895	0.8758	0.344	0.7895		
6	6	7	0.3697	0.1954	0.0848	0.2992	0.8157	0.0346	0.1331	0.8157		
6	6	8	0.4083	0.0851	0.0405	0.2312	0.6264	0.6421	0.1087	0.6264		
6	7	8	0.9435	0.6621	0.7359	0.872	0.7994	0.096	0.9168	0.7994		
7	5	6	0.6998	0.8745	0.797	0.8725	0.0855	0.6681	0.767	0.0855		
7	5	7	0.2484	0.1242	0.0338	0.2657	0.3495	0.3323	0.0312	0.3495		
7	5	8	0.1667	0.1197	0.0351	0.3523	0.9798	0.7882	0.0118	0.9798		
7	6	7	0.1064	0.128	0.0393	0.1763	0.4777	0.1442	0.0458	0.4777		

## Appendix H. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	Org-N	p-values	
7	6	8	0.0581	0.119	0.0395	0.4031	0.059	0.8644	0.017	0.059		
7	7	8	0.8699	0.9034	0.8385	0.0356	0.3187	0.1943	0.7806	0.3187		
8	5	6	0.6408	0.7209	0.6008	0.9296	0.2827	0.4509	0.6963	0.2827		
8	5	7	0.4376	0.3563	0.3129	0.7342	0.1906	0.6403	0.6705	0.1906		
8	5	8	0.5079	0.0817	0.103	0.4382	0.1138	0.2111	0.4936	0.1138		
8	6	7	0.1838	0.1678	0.0999	0.645	0.797	0.7572	0.3841	0.797		
8	6	8	0.2384	0.0272	0.0245	0.4595	0.5294	0.5691	0.2606	0.5294		
8	7	8	0.9307	0.3389	0.4583	0.2409	0.6953	0.3885	0.7701	0.6953		
9	5	6	0.6537	0.6367	0.5587	0.1112	0.7475	0.4827	0.1521	0.7475		
9	5	7	0.5894	0.6442	0.955	0.7373	0.6386	0.7228	0.747	0.6386		
9	5	8	0.5996	0.9295	0.9545	0.6845	0.6711	0.3641	0.4404	0.6711		
9	6	7	0.2909	0.3147	0.4657	0.1398	0.4008	0.6635	0.0536	0.4008		
9	6	8	0.9795	0.5263	0.4653	0.1598	0.4264	0.8954	0.4063	0.4264		
9	7	8	0.2122	0.647	0.9994	0.9329	0.9558	0.5143	0.2066	0.9558		
10	6	7	0.9233	0.4813	0.6505	0.4494	0.4785	0.955	0.6735	0.4785		
10	6	8	0.771	0.9207	0.9115	0.9697	0.6932	0.9792	0.7344	0.6932		
10	7	8	0.7972	0.4093	0.75	0.4163	0.8194	0.929	0.4013	0.8194		
11	5	6	0.6244	0.5659	0.8391	0.5042	0.8338	0.656	0.6614	0.8338		
11	5	7	0.81	0.3437	0.9909	0.6791	0.9994	0.2563	0.8399	0.9994		
11	5	8	0.9024	0.3963	0.8776	0.7388	0.8236	0.1776	0.5001	0.8236		
11	6	7	0.7193	0.8025	0.8129	0.6894	0.7975	0.5456	0.7384	0.7975		
11	6	8	0.7115	0.7829	0.9608	0.7359	0.9896	0.3618	0.8123	0.9896		
11	7	8	0.9267	0.9321	0.8598	0.992	0.7852	0.613	0.5319	0.7852		
12	6	7	0.6959	0.8335	0.9866	0.5525	0.9106	0.8271	0.6938	0.9106		
12	6	8	0.9183	0.7136	0.7909	0.8601	0.9178	0.9835	0.9118	0.9178		



## Appendix H. Continued.

Sampling time	Treatment	Treatment	NO <sub>3</sub> -N	NH <sub>4</sub> -N	TKN	PO <sub>4</sub> -P	TKP	pH	EC	Org-N
12	7	8	0.6172	0.8747	0.7763	0.6824	0.8294	0.8099	0.607	0.6683
13	5	6	0.517	0.6636	0.8749	0.743	0.6683	0.3669	0.627	0.0386
13	5	7	0.3547	0.5893	0.9925	0.2361	0.0386	0.2304	0.4246	0.0103
13	6	7	0.8921	0.9915	0.8401	0.114	0.0103	0.9134	0.8333	0.9538
15	5	6	0.4546	0.6317	0.5345	0.8313	0.9538	0.9684	0.9112	0.9209
15	5	7	0.9723	0.5497	0.5621	0.8455	0.9209	0.4383	0.8026	0.982
15	5	8	0.7383	0.8478	0.9469	0.9504	0.982	0.7515	0.5079	0.9238
15	6	7	0.338	0.908	0.9205	0.969	0.9616	0.3519	0.8677	0.0548
15	6	8	0.1872	0.4129	0.4006	0.8538	0.9655	0.7352	0.5001	0.0982
15	7	8	0.6228	0.3103	0.4106	0.8697	0.9238	0.5751	0.5669	0.0214
22	5	6	0.8289	0.03	0.0005	0.3767	0.0548	0.9054	0.3996	0.7825
22	5	7	0.3503	0.6323	0.3916	0.5664	0.0982	0.8886	0.8635	0.691
22	5	8	0.0694	0.4837	0.8173	0.1629	0.0214	0.4461	0.3994	0.5011
22	6	7	0.4719	0.0874	0.0067	0.1471	0.7825	0.983	0.3112	0.9689
22	6	8	0.1082	0.0047	0.001	0.6047	0.691	0.5198	0.0943	0.783
22	7	8	0.3696	0.2401	0.5308	0.0508	0.5011	0.5336	0.5017	0.7825
24	6	7	0.7573	0.6513	0.686	0.5483	0.9689	0.7572	0.703	0.691
27	6	7	0.1889	0.9437	0.9776	0.1558	0.783	0.8695	0.0127	0.7825
28	5	6	0.3335	0.2638	0.527	0.269	0.9297	0.3294	0.3676	0.9297
28	5	7	0.6853	0.6732	0.6893	0.5983	0.9915	0.7129	0.44	0.9915
28	5	8	0.2292	0.8866	0.9066	0.0565	0.9751	0.5505	0.4133	0.9751
28	6	7	0.1601	0.1177	0.2865	0.0963	0.9207	0.172	0.0831	0.9207
28	6	8	0.0242	0.2033	0.4468	0.3118	0.9571	0.1049	0.0747	0.9571
28	7	8	0.423	0.7799	0.7775	0.016	0.9665	0.8187	0.9631	0.9665

**Appendix I. Differences of least squares means in time series analysis for Eh.**

Sampling time	Treatment	Treatment	Eh p-values
10-Aug-06	1	6	<.0001
10-Aug-06	1	8	<.0001
10-Aug-06	6	8	0.0608
8-Sep-06	1	6	<.0001
8-Sep-06	1	8	<.0001
8-Sep-06	6	8	0.5945
6-Oct-06	1	6	<.0001
6-Oct-06	1	8	<.0001
6-Oct-06	6	8	0.9317
3-Nov-06	1	6	<.0001
3-Nov-06	1	8	<.0001
3-Nov-06	6	8	0.9628
1-Dec-06	1	6	<.0001
1-Dec-06	1	8	<.0001
1-Dec-06	6	8	0.8761
19-Jan-07	1	6	<.0001
19-Jan-07	1	8	<.0001
19-Jan-07	6	8	0.8582
2-Mar-07	1	6	<.0001
2-Mar-07	1	8	<.0001
2-Mar-07	6	8	0.6599
13-Apr-07	1	6	<.0001
13-Apr-07	1	8	<.0001
13-Apr-07	6	8	0.1813
11-May-07	1	6	<.0001
11-May-07	1	8	<.0001
11-May-07	6	8	0.1038
8-Jun-07	1	6	<.0001
8-Jun-07	1	8	<.0001
8-Jun-07	6	8	0.1439
10-Jul-07	1	6	<.0001
10-Jul-07	1	8	<.0001
10-Jul-07	6	8	0.3533
9-Aug-07	1	6	<.0001
9-Aug-07	1	8	<.0001
9-Aug-07	6	8	0.1458
28-Dec-08	1	6	0.0019
28-Dec-08	1	8	<.0001
28-Dec-08	6	8	<.0001

**Appendix J. Differences of least squares means in time series analysis for GHG emissions at each sampling event throughout the study (October 2006-April 2009).**

Sampling time	Treatment	Treatment	N <sub>2</sub> O	CH <sub>4</sub> p-values	CO <sub>2</sub>
6-Oct-06	1	4	1		
6-Oct-06	1	6	<.0001		
6-Oct-06	1	8	<.0001		
6-Oct-06	4	6	<.0001		
6-Oct-06	4	8	<.0001		
6-Oct-06	6	8	0.7363		
3-Nov-06	1	4	1		
3-Nov-06	1	6	<.0001		
3-Nov-06	1	8	<.0001		
3-Nov-06	4	6	<.0001		
3-Nov-06	4	8	<.0001		
3-Nov-06	6	8	0.0016		
15-Dec-06	1	4	1		
15-Dec-06	1	6	<.0001		
15-Dec-06	1	8	0.0012		
15-Dec-06	4	6	<.0001		
15-Dec-06	4	8	0.0012		
15-Dec-06	6	8	<.0001		
5-Jan-07	1	4	1		
5-Jan-07	1	6	0.0009		
5-Jan-07	1	8	0.0349		
5-Jan-07	4	6	0.0009		
5-Jan-07	4	8	0.0349		
5-Jan-07	6	8	0.1059		
9-Feb-07	1	4	1		
9-Feb-07	1	6	0.0008		
9-Feb-07	1	8	0.028		
9-Feb-07	4	6	0.0008		
9-Feb-07	4	8	0.028		
9-Feb-07	6	8	0.1219		
2-Mar-07	1	4	0.8872		
2-Mar-07	1	6	0.0887		
2-Mar-07	1	8	0.3553		
2-Mar-07	4	6	0.0613		
2-Mar-07	4	8	0.2741		
2-Mar-07	6	8	0.3023		

**Appendix J. Continued.**

Sampling time	Treatment	Treatment	N <sub>2</sub> O	CH <sub>4</sub> p-values	CO <sub>2</sub>
5-Mar-07	1	4	0.6362		
5-Mar-07	1	6	0.0098		
5-Mar-07	1	8	0.3434		
5-Mar-07	4	6	0.0017		
5-Mar-07	4	8	0.1306		
5-Mar-07	6	8	0.0301		
23-Mar-07	1	4	1		
23-Mar-07	1	6	<.0001		
23-Mar-07	1	8	0.0001		
23-Mar-07	4	6	<.0001		
23-Mar-07	4	8	0.0001		
23-Mar-07	6	8	<.0001		
13-Apr-07	1	4	0.0319		
13-Apr-07	1	6	<.0001		
13-Apr-07	1	8	<.0001		
13-Apr-07	4	6	<.0001		
13-Apr-07	4	8	0.0055		
13-Apr-07	6	8	0.0015		
11-May-07	1	4	0.2262		
11-May-07	1	6	<.0001		
11-May-07	1	8	0.002		
11-May-07	4	6	<.0001		
11-May-07	4	8	<.0001		
11-May-07	6	8	<.0001		
8-Jun-07	1	4	<.0001		
8-Jun-07	1	6	<.0001		
8-Jun-07	1	8	<.0001		
8-Jun-07	4	6	<.0001		
8-Jun-07	4	8	<.0001		
8-Jun-07	6	8	0.0003		
10-Jul-07	1	4	0.0073		
10-Jul-07	1	6	<.0001		
10-Jul-07	1	8	<.0001		
10-Jul-07	4	6	<.0001		
10-Jul-07	4	8	<.0001		
10-Jul-07	6	8	<.0001		

**Appendix J. Continued.**

Sampling time	Treatment	Treatment	N <sub>2</sub> O	CH <sub>4</sub> p-values	CO <sub>2</sub>
9-Aug-07	1	4	0.1569		
9-Aug-07	1	6	<.0001		
9-Aug-07	1	8	<.0001		
9-Aug-07	4	6	<.0001		
9-Aug-07	4	8	<.0001		
9-Aug-07	6	8	<.0001		
7-Sep-07	1	4	0.2061		
7-Sep-07	1	6	<.0001		
7-Sep-07	1	8	<.0001		
7-Sep-07	4	6	<.0001		
7-Sep-07	4	8	<.0001		
7-Sep-07	6	8	<.0001		
2-May-08	1	4	<.0001		
2-May-08	1	6	<.0001		
2-May-08	1	8	<.0001		
2-May-08	4	6	<.0001		
2-May-08	4	8	0.5705		
2-May-08	6	8	<.0001		
5-Jun-08	1	4	<.0001		
5-Jun-08	1	6	<.0001		
5-Jun-08	1	8	<.0001		
5-Jun-08	4	6	<.0001		
5-Jun-08	4	8	0.0839		
5-Jun-08	6	8	<.0001		
11-Jul-08	1	4	0.03		
11-Jul-08	1	6	<.0001		
11-Jul-08	1	8	<.0001		
11-Jul-08	4	6	<.0001		
11-Jul-08	4	8	<.0001		
11-Jul-08	6	8	<.0001		
26-Sep-08	1	4	0.3511		
26-Sep-08	1	6	<.0001		
26-Sep-08	1	8	<.0001		
26-Sep-08	4	6	<.0001		
26-Sep-08	4	8	<.0001		
26-Sep-08	6	8	<.0001		

**Appendix J. Continued.**

Sampling time	Treatment	Treatment	N <sub>2</sub> O	CH <sub>4</sub> p-values	CO <sub>2</sub>
23-Oct-08	1	4	<.0001		
23-Oct-08	1	6	<.0001		
23-Oct-08	1	8	<.0001		
23-Oct-08	4	6	<.0001		
23-Oct-08	4	8	<.0001		
23-Oct-08	6	8	0.0031		
28-Dec-08	1	4	0.0594	0.5602	0.045
28-Dec-08	1	6	<.0001	0.0737	0.0019
28-Dec-08	1	8	<.0001	0.0161	<.0001
28-Dec-08	4	6	<.0001	0.2179	0.2105
28-Dec-08	4	8	<.0001	0.0607	0.0039
28-Dec-08	6	8	<.0001	0.4993	0.0794
8-Apr-09	1	4	<.0001	0.5185	0.4102
8-Apr-09	1	6	<.0001	0.0932	0.6625
8-Apr-09	1	8	<.0001	0.9616	0.0264
8-Apr-09	4	6	<.0001	0.0229	0.6965
8-Apr-09	4	8	0.3152	0.5498	0.1468
8-Apr-09	6	8	<.0001	0.0847	0.0688

**Appendix K. Hybrid poplar leaf area and foliar N and P.**

Treatment	LA, cm <sup>2</sup>	P, mg g <sup>-1</sup>	TKN, mg g <sup>-1</sup>
105-T1	3688	2.3525	26.75
206-T1	3773	2.675	28.25
307-T1	2942	2.1375	27
404-T1	3109	2.305	28
101-T2	2919	1.9725	23.45
208-T2	3024	2.55	29.5
302-T2	3723	2.25	31.75
403-T2	3052	2.0575	30
102-T3	3212	2.4125	38.5
203-T3	3718	2.335	31
304-T3	2948	1.975	28.75
407-T3	4173	2.41	36
108-T4	2979	2.425	30
202-T4	4752	2.575	27.5
305-T4	3555	2.4725	29.75
402-T4	3660	2.525	30.75
103-T5	3779	2.65	30.75
204-T5	4267	3.175	34.25
308-T5	2870	3.05	33.75
406-T5	4363	2.675	31.75
107-T6	4546	2.4075	32.25
205-T6	4782	3.575	32
303-T6	3885	3.6	35.5
401-T6	4766	3.925	35.75
106-T7	3407	2.2725	28.5
201-T7	3804	2.325	26
306-T7	3982	2.675	30
405-T7	4280	2.4975	28.75
104-T8	3692	2.47	27.75
207-T8	4687	2.3925	27
301-T8	3237	2.13	24.4
408-T8	3560	1.95	25.25

**Appendix L. Hybrid poplar foliar micronutrient concentrations.**

Treatment	Al	B	Ca	Cu	Fe	K mg g <sup>-1</sup>	Mg	Mn	Mo	S	Zn
105-T1	18.350	42.569	10.322	1.664	74.628	13.600	3.194	198.307	0.004	3.028	125.036
206-T1	46.190	116.259	28.581	10.476	170.476	32.895	8.941	542.041	0.612	8.385	380.408
307-T1	38.731	63.808	12.699	3.483	71.842	17.754	4.476	330.186	0.004	3.391	240.139
404-T1	21.062	40.893	11.357	2.895	64.885	17.303	3.730	248.794	0.004	3.404	173.088
101-T2	16.330	28.505	7.155	1.823	44.435	8.462	2.270	175.079	0.004	2.142	132.211
208-T2	16.361	39.978	9.556	4.737	65.812	13.934	2.777	241.209	0.004	3.696	189.003
302-T2	22.248	41.972	7.570	1.972	59.725	13.389	2.858	183.028	0.004	3.241	153.349
403-T2	30.685	74.840	12.768	5.799	98.356	22.800	4.709	266.301	0.004	5.807	256.164
102-T3	20.115	52.846	12.891	5.154	73.500	16.174	3.182	178.692	0.615	3.233	87.423
203-T3	24.194	21.213	11.612	2.594	78.619	17.748	3.127	57.058	0.004	3.441	45.484
304-T3	19.634	25.131	10.397	4.005	84.188	21.412	3.465	65.812	0.903	3.926	48.848
407-T3	25.861	47.316	12.273	3.190	76.177	16.393	3.463	198.494	0.004	3.885	151.747
108-T4	19.520	27.571	14.638	3.598	93.058	23.740	3.363	68.951	0.675	3.980	56.582
202-T4	13.843	24.652	9.173	2.693	61.479	17.036	2.581	57.838	0.004	3.191	42.137
305-T4	23.917	24.083	11.497	2.772	77.503	20.573	3.477	144.703	0.004	3.445	48.414
402-T4	29.927	16.416	9.474	1.126	71.404	16.305	3.178	60.145	0.004	2.993	30.436
103-T5	29.197	27.132	24.518	9.350	104.512	27.271	5.955	99.120	0.004	5.011	23.403
204-T5	11.845	8.031	6.219	2.092	38.639	9.531	1.852	28.144	0.004	1.921	26.490
308-T5	25.577	22.031	11.803	4.089	84.242	19.487	4.350	112.907	0.004	3.681	35.049
406-T5	36.024	34.367	12.685	4.326	111.226	28.497	4.579	149.838	0.004	4.206	28.666
107-T6	51.625	69.199	40.870	1.304	154.256	39.086	10.882	188.924	1.167	7.977	20.114
205-T6	26.645	11.684	16.637	1.118	84.987	23.358	5.550	49.049	1.542	4.382	19.704
303-T6	63.526	36.474	22.325	3.397	123.141	29.882	6.983	238.077	0.004	5.711	111.603
401-T6	28.761	17.497	11.339	0.255	83.001	17.959	3.400	125.140	0.004	3.135	16.804
106-T7	54.550	14.198	18.816	0.003	110.748	23.682	6.797	188.565	0.004	3.832	24.595
201-T7	48.408	22.928	14.485	0.401	79.830	17.421	4.861	145.371	0.583	3.120	17.825
306-T7	39.988	18.173	12.206	3.534	96.130	18.043	4.399	167.236	0.004	3.561	68.113



**Appendix L. Continued.**

Treatment	Al	B	Ca	Cu	Fe	K mg g <sup>-1</sup>	Mg	Mn	Mo	S	Zn
405-T7	39.601	18.194	14.304	1.457	98.443	23.301	3.762	146.750	0.822	4.176	25.442
104-T8	29.737	12.685	15.483	1.317	73.551	14.836	5.898	112.171	1.731	1.912	17.804
207-T8	36.827	30.117	14.450	0.003	82.276	16.962	5.171	80.247	0.004	3.924	15.449
301-T8	31.378	18.247	15.145	0.003	65.333	15.365	4.958	98.742	0.834	2.408	12.007
408-T8	45.659	21.183	11.002	0.003	83.488	22.353	4.210	165.183	0.004	3.759	31.354

**Appendix M. Hybrid poplar growth parameters measurements.**

Treatment	block	tree ID	DBH, cm	BD, cm	HT, m
1	1	1	4.2	6.5	4.6
1	1	2	6	8.5	5.8
1	1	3	4.1	5.9	4.6
1	1	4	5	7.2	4.7
1	1	5	6.4	8.8	5.6
1	1	6	6.5	10.8	5.7
1	1	7	7.8	10.3	6.3
1	1	8	5.1	6.8	5.1
1	1	9	5.5	7.6	4.7
1	1	10	3	4.8	4.0
1	2	1	5.7	9.7	5.6
1	2	2	8.4	12.9	6.7
1	2	3	5	7.3	5.0
1	2	4	2.7	4.6	3.0
1	2	5	3.6	6.5	3.4
1	2	6	5	10.5	5.0
1	2	7	5.9	8.5	5.4
1	2	8	3.7	5.8	4.5
1	2	9	1.8	4.1	3.5
1	2	10	3.7	7.3	3.7
1	3	1	3.7	9.1	3.9
1	3	2	4.5	6.9	4.4
1	3	3	4.2	7.1	4.3
1	3	4	5.2	8.3	4.6
1	3	5	4.5	7.1	4.3
1	3	6	2.6	4.9	3.4
1	3	7	4.3	8	4.7
1	3	8	3.8	5.8	4.1
1	3	9	2.4	4.1	3.0
1	3	10	3.2	6.2	3.7
1	4	1	4.6	7.6	4.4
1	4	2	3.4	6.1	4.0
1	4	3	4	7	4.1
1	4	4	3.4	6.9	3.5
1	4	5	2.5	6.1	3.4
1	4	6	3.9	8.9	4.1
1	4	7	2.5	8.5	3.2

## Appendix M. Continued.

Treatment	block	tree ID	DBH, cm	BD, cm	HT, m
1	4	8	3.8	7.2	4.0
1	4	9	4	6.8	4.4
1	4	10	3.5	7.3	3.8
2	1	1	6.6	9.8	5.2
2	1	2			
2	1	3	4.1	6.1	4.1
2	1	4	4.4	6.6	4.4
2	1	5	4.8	6.9	5.0
2	1	6	7.6	12	5.5
2	1	7	4.8	7.3	4.3
2	1	8	4	6.2	4.6
2	1	9	5.9	8.2	5.2
2	1	10	7.2	9.2	5.7
2	2	1	2.6	6.2	3.3
2	2	2			
2	2	3	1.6	3.9	2.8
2	2	4	8.5	11.6	6.1
2	2	5	1.9	3.5	2.6
2	2	6	1.9	3.1	2.6
2	2	7	4.4	5.8	3.8
2	2	8	3	6.2	3.2
2	2	9	2.3	3.9	2.6
2	2	10	2.5	4.4	3.0
2	3	1	4	7.5	3.7
2	3	2	4.1	6.2	3.9
2	3	3	4.8	8.9	4.4
2	3	4	4.8	7.2	4.6
2	3	5	4.2	6.2	3.7
2	3	6	3.1	4.9	3.2
2	3	7	3.6	6.7	3.4
2	3	8	3.1	4.6	3.8
2	3	9	4.6	6.7	4.1
2	3	10	5.2	7.7	4.5
2	4	1	5.8	9	4.6
2	4	2	5.5	8.8	4.6
2	4	3	4.2	8.8	4.1
2	4	4	4	7.5	4.1

## Appendix M. Continued.

Treatment	block	tree ID	DBH, cm	BD, cm	HT, m
2	4	5	4.3	7.7	4.3
2	4	6	3.7	5.3	4.0
2	4	7	4.1	8.8	4.4
2	4	8			
2	4	9	3.1	5.4	3.4
2	4	10			
3	1	1	2.3	4.8	2.7
3	1	2	2	3.4	2.6
3	1	3	3.6	5.2	4.0
3	1	4	4.8	7.2	4.6
3	1	5	2.1	3.7	2.7
3	1	6	5.3	7.6	5.2
3	1	7	2.4	5.3	2.8
3	1	8	4.1	6.2	3.7
3	1	9	2.2	3.4	2.6
3	1	10	2.8	5.2	3.0
3	2	1	4.6	8.7	5.4
3	2	2			
3	2	3	2.6	4.8	3.4
3	2	4			
3	2	5	4	6.8	4.1
3	2	6	4	6.8	5.1
3	2	7	2.6	4.7	3.1
3	2	8			
3	2	9	3.3	5.9	3.4
3	2	10			
3	3	1			
3	3	2			
3	3	3	5.2	10	4.6
3	3	4	6	9.4	4.6
3	3	5	3.4	5.3	3.2
3	3	6	5.3	7.7	4.4
3	3	7	7.5	11.5	5.0
3	3	8	3.8	5.9	3.6
3	3	9			
3	3	10	6	7.9	4.4
3	4	1	3.9	6.5	4.0

## Appendix M. Continued.

Treatment	block	tree ID	DBH, cm	BD, cm	HT, m
3	4	2	4	7.1	4.0
3	4	3	2.7	4.8	3.1
3	4	4	3.4	8.7	3.7
3	4	5	6.6	10.7	4.3
3	4	6	2.5	7.6	3.0
3	4	7	2.2	4.6	2.6
3	4	8	3.4	6.7	3.1
3	4	9	3.6	6.8	3.7
3	4	10	3	5.3	3.4
4	1	1			
4	1	2			
4	1	3	2.6	4.1	3.0
4	1	4			
4	1	5	1.6	2.8	2.4
4	1	6	3.8	6.3	3.8
4	1	7	2.3	5.5	3.0
4	1	8	3.5	5.5	3.7
4	1	9	3.6	5.7	3.5
4	1	10	3.7	6.2	3.6
4	2	1	2.3	5.6	3.0
4	2	2	2	3.8	2.5
4	2	3	3.2	6.6	4.1
4	2	4	2.4	5.6	3.6
4	2	5	4.4	8.2	4.2
4	2	6	2.8	5.2	3.4
4	2	7	2.7	5.2	3.4
4	2	8			
4	2	9			
4	2	10	3.2	6	3.8
4	3	1	2.7	4.6	3.3
4	3	2			
4	3	3	2.8	4.9	3.4
4	3	4			
4	3	5	3.7	5.9	3.5
4	3	6	2.2	3.7	2.4
4	3	7	1.7	3	2.3
4	3	8	2.4	4.3	3.0

## Appendix M. Continued.

Treatment	block	tree ID	DBH, cm	BD, cm	HT, m
4	3	9	3.4	6.1	3.7
4	3	10	2.3	4.2	2.7
4	4	1	4.1	7.1	4.0
4	4	2			2.0
4	4	3	3.5	5.7	3.7
4	4	4			
4	4	5			
4	4	6	2	3.9	2.6
4	4	7	3.3	7.1	3.2
4	4	8	4.5	7.4	4.3
4	4	9	4.6	6.9	3.8
4	4	10			
5	1	1			
5	1	2	3.4	5.8	3.0
5	1	3	4.1	7.2	4.3
5	1	4	4	6.6	3.8
5	1	5	2.2	4	2.8
5	1	6	5.4	9	4.4
5	1	7	5.1	8.5	5.4
5	1	8	4	8.9	4.6
5	1	9	4.4	8.1	4.4
5	1	10	3.7	7	3.7
5	2	1	3.3	8.3	3.6
5	2	2	3.8	6.4	4.0
5	2	3	4.8	11.9	5.0
5	2	4	5.7	12.3	5.7
5	2	5	3	5.9	3.4
5	2	6	6.2	10.2	5.1
5	2	7	7.2	11.4	6.0
5	2	8	4.8	11.7	5.7
5	2	9	6.7	10	5.7
5	2	10	3.9	6.5	3.4
5	3	1	4	9.2	4.1
5	3	2	8.4	12.4	6.3
5	3	3	6.1	9.2	4.3
5	3	4	4.5	10.1	3.8
5	3	5	6.1	10.1	4.7

## Appendix M. Continued.

Treatment	block	tree ID	DBH, cm	BD, cm	HT, m
5	3	6	6.2	9.3	4.1
5	3	7	4.7	7.2	4.0
5	3	8	5.2	8.1	4.4
5	3	9	3.3	9.4	4.0
5	3	10	3.6	8.2	4.1
5	4	1	2.5	6.5	3.4
5	4	2			
5	4	3	7.6	12.3	5.0
5	4	4	3.5	7.1	3.8
5	4	5	5	12.3	5.2
5	4	6	4.3	10.2	4.2
5	4	7			
5	4	8	6.9	9.9	5.6
5	4	9	8.3	13.7	5.8
5	4	10	3.5	8.7	3.8
6	1	1	5.1	7.4	4.1
6	1	2	4.1	7	4.0
6	1	3	5.9	9	5.6
6	1	4	8	10.8	5.7
6	1	5	3.7	8.8	3.8
6	1	6	3.6	5.9	3.8
6	1	7	8.8	11.5	6.3
6	1	8	4.1	9.4	4.4
6	1	9	6.2	11.2	5.3
6	1	10	5	7	4.2
6	2	1	7.7	11	6.6
6	2	2	10.2	14.7	6.9
6	2	3	6.7	10.9	5.9
6	2	4			
6	2	5			
6	2	6			
6	2	7	2.8	5.7	3.8
6	2	8	4.3	7.1	4.5
6	2	9	2.4	6	3.0
6	2	10			
6	3	1	4.4	6.8	3.8
6	3	2	4.5	6.6	3.8

## Appendix M. Continued.

Treatment	block	tree ID	DBH, cm	BD, cm	HT, m
6	3	3	6.5	10.5	4.8
6	3	4	6.1	9	5.3
6	3	5	5.4	9.2	4.4
6	3	6			
6	3	7	4.5	7.1	3.5
6	3	8	4.6	6.3	4.5
6	3	9	3.7	6.6	3.5
6	3	10			
6	4	1	3.5	10	3.5
6	4	2	2.1	5	3.1
6	4	3	8.5	11.3	6.1
6	4	4	5	8.4	4.6
6	4	5	3.7	4.9	3.0
6	4	6	4.1	9.5	3.5
6	4	7	3.5	6.5	3.4
6	4	8	3.5	6.2	3.7
6	4	9	6.1	8.9	5.4
6	4	10	4.6	7.4	4.0
7	1	1	5.7	8.3	4.6
7	1	2	4.9	9.2	4.7
7	1	3			
7	1	4	5.6	8.7	4.7
7	1	5	6	9	5.0
7	1	6	5.5	9.8	5.0
7	1	7	5.8	9.5	5.0
7	1	8	4.6	7.3	4.3
7	1	9	6.5	10.3	5.8
7	1	10	8.1	12.5	6.3
7	2	1	5	10.8	5.0
7	2	2	5.1	10.3	4.6
7	2	3	6.7	11.3	5.2
7	2	4	6	9.3	4.7
7	2	5	3.2	7.3	3.3
7	2	6	3.2	6.4	3.5
7	2	7	5.9	12	5.5
7	2	8	2	4.2	2.6
7	2	9	4.5	7.5	4.3



## Appendix M. Continued.

Treatment	block	tree ID	DBH, cm	BD, cm	HT, m
7	2	10	4	7.8	3.8
7	3	1	3.9	7.3	3.8
7	3	2	3.6	8.5	3.9
7	3	3	4.4	7.3	4.3
7	3	4	7.7	10.9	6.3
7	3	5	4.1	6.8	4.0
7	3	6	2.7	4.6	2.9
7	3	7	1.8	4.9	2.4
7	3	8	5.8	8.8	5.2
7	3	9			
7	3	10	2.6	4.8	3.0
7	4	1	3.8	6.2	4.0
7	4	2	6.2	9.2	5.1
7	4	3	5.8	8.2	5.3
7	4	4	2.8	5.5	3.4
7	4	5	3	5.5	2.6
7	4	6	5.9	9.6	5.5
7	4	7	5.2	8.2	5.0
7	4	8	8.3	14.4	6.4
7	4	9	3.5	6.3	3.7
7	4	10	5.2	7.7	3.9
8	1	1	4.2	7.5	3.9
8	1	2			
8	1	3	6	8.8	4.9
8	1	4	3.2	6.3	3.7
8	1	5			
8	1	6	2.9	5.1	2.1
8	1	7	2.9	5.1	3.8
8	1	8	5	9.6	4.3
8	1	9			
8	1	10	2.5	6.9	4.1
8	2	1	3.4	5.5	3.1
8	2	2	3.1	4.7	3.2
8	2	3	3.1	6.5	3.5
8	2	4			
8	2	5	5.2	10	4.1
8	2	6	4.7	7.3	4.4

## Appendix M. Continued.

Treatment	block	tree ID	DBH, cm	BD, cm	HT, m
8	2	7	4.4	10	5.0
8	2	8	3	3.6	2.7
8	2	9	2.3	7.7	3.8
8	2	10	2.5	4.8	2.9
8	3	1	4.1	5.7	3.5
8	3	2	2.8	5.6	3.5
8	3	3	5.1	8.2	4.3
8	3	4	5.2	7.9	4.4
8	3	5	3.4	6.9	3.4
8	3	6			
8	3	7	4.4	7.2	3.8
8	3	8	5	9.9	4.3
8	3	9	5.1	8.7	4.4
8	3	10	5	8	4.1
8	4	1	4.2	7.2	3.4
8	4	2	2.2	4.1	2.9
8	4	3	6.1	10	4.7
8	4	4	2.7	5.3	2.9
8	4	5	2.9	5.4	3.1
8	4	6	4.1	8	3.7
8	4	7	5.4	8.8	4.0
8	4	8	3.5	6.4	3.3
8	4	9	3.3	9.5	3.3
8	4	10	3.1	5.3	3.0

**Appendix N. Soil pH and soil test Mehlich 1 extractable elements (May 2009).**

Treatment	pH	P	K	Ca	Mg mg kg <sup>-1</sup>	Zn	Mn	Cu
105-T1	7.34	49	55	384	72	1	3.1	0.4
206-T1	7.31	35	36	341	63	1	3.3	0.4
307-T1	6.01	38	88	336	65	0.6	3	0.3
404-T1	6.13	44	128	468	97	0.7	3.3	0.3
101-T2	6.58	51	60	301	79	0.5	3.9	0.2
208-T2	7	77	46	456	85	2.2	6.3	0.3
302-T2	6.52	54	75	471	78	1.4	3.4	0.5
403-T2	5.71	52	141	476	81	0.9	4.6	0.4
102-T3	6.71	68	85	389	91	0.7	4.8	0.2
203-T3	5.58	33	47	184	47	0.5	4	0.2
304-T3	5.03	37	113	280	61	0.8	3.7	0.3
407-T3	5.89	87	95	383	58	1.4	3.5	0.5
108-T4	7.07	101	34	443	61	0.8	3.6	0.2
202-T4	6.85	55	42	405	87	0.5	5.6	0.2
305-T4	6.83	54	25	253	42	0.7	2.5	0.1
402-T4	5.29	72	80	305	50	1.1	2.6	0.2

**Appendix O. Entrenched biosolids P fractions and Mehlich 1(M 1) extractable P, Al, Ca and Fe.**

Treatment	block	depth	KCl_P	NaOH_P	HCl_P	TKP	M1 P	M1 Al	M1 Ca	M1 Fe
							mg kg <sup>-1</sup>			
ADa	1	1	23.25	18450	3166.38	24766	1444.83	4403.4	16582.11	2284.08
ADa	1	2	20.04	18259.74	3504.66	26251	1461.03	4622.61	13208.43	2050.41
ADa	1	3	21.06	16671.75	3060.78	36832	877.17	3334.47	18725.4	1276.77
ADa	1	4	19.26	14729.19	2749.17	30957	1695.51	4071.21	13491.93	2004.6
ADa	1	5	27.18	13899.18	4801.8	26512	1817.94	4035.54	16876.59	2772.48
ADa	1	6	16.62	16560.77	2188.34	18883	1765.56	5437.62	15499.62	2164.17
ADa	2	1	19.92	17481.96	3071.52	23421	1443.3	3836.67	8529.75	2398.14
ADa	2	2	15.36	17030.19	2788.89	26127	1760.88	5119.35	13401.66	2280.9
ADa	2	3	15.33	14991.75	2767.56	23471	1602.6	4191.21	12776.37	2222.37
ADa	2	4	24.45	17040.87	3140.94	26900	1884.36	4673.64	8236.14	2535.39
ADa	2	5	25.41	12149.76	4524.06	32388	1428.09	3876.78	18249.75	2013.3
ADa	2	6	28.14	14694.48	5172.69	27874	2101.8	3823.2	15311.61	4686.78
ADa	3	1	20.61	16978.95	2691.93	25249	1558.86	4717.32	7071.06	2241.69
ADa	3	2	17.1	16847.43	2896.95	25882	1930.95	5159.91	11980.53	2404.77
ADa	3	3	18	17669.31	3083.7	28736	1835.52	5410.14	8011.74	2294.64
ADa	3	4	21.42	18776.79	3028.86	23128	1584.69	4307.7	6868.77	2190.27
ADa	3	5	22.74	15590.22	4080.27	35980	1127.07	3904.56	18682.86	1571.01
ADa	3	6	28.86	14126.52	6001.38	27106	1535.7	4201.89	18802.56	1784.7
ADa	4	1	18	10602.33	3288.42	23330	1833.66	5033.52	15347.97	2516.37
ADa	4	2	18.93	18156.51	3073.92	28939	1414.14	4639.56	13918.44	1491.87
ADa	4	3	23.94	16182.06	4700.64	24025	1177.5	4206.45	23045.97	849.63
ADa	4	4	14.88	11983.74	1567.98	22209	1597.98	4275.57	15451.83	1733.19
ADa	4	5	29.94	12899.04	5820.6	24681	1603.62	4164.66	17120.91	2052.18
ADa	4	6	19.41	10140.33	2593.91	13003	1224.72	4323.15	15526.56	1336.11
LSa	1	1	75.75	423.99	5418.21	5973	75.24	12.84	56919.3	77.82
LSa	1	2	142.44	187.8	4954.92	5325	169.41	2.34	65154	55.29

## Appendix O. Continued.

Treatment	block	depth	KCl_P	NaOH_P	HCl_P	TKP	M1 P mg kg <sup>-1</sup>	M1 Al	M1 Ca	M1 Fe
LSa	1	3	83.01	74.61	2850.42	8046	66.51	3	57720.3	137.04
LSa	1	4	103.38	282.15	5649.6	7197	417.66	4.14	58476	75.51
LSa	1	5	120.12	180.54	3911.19	4261	223.5	5.19	64933.8	63.57
LSa	1	6	118.74	151.2	5860.98	22980	214.5	2.82	67453.8	68.13
LSa	2	1	44.46	604.59	6698.64	7390	64.62	0.12	48065.1	62.73
LSa	2	2	87.75	252.06	6801.48	11930	177.51	3.09	56583.6	211.89
LSa	2	3	87.18	254.79	6762.3	9168	264.03	1.71	53418.3	234.87
LSa	2	4	45.66	142.32	2346.66	4912	700.26	22.26	39908.1	1241.61
LSa	2	5	231.33	244.53	5005.23	10140	341.55	4.77	68951.1	73.71
LSa	2	6	257.07	304.26	5583.9	15262	361.83	3.33	67944.9	67.08
LSa	3	1	69.3	470.73	4854.81	5494	104.25	0.12	45855	99.45
LSa	3	2	163.41	281.22	6289.32	7540	309.63	1.65	61086	97.02
LSa	3	3	162.93	175.8	3835.5	7631	310.11	2.64	61762.2	53.94
LSa	3	4	55.11	168.06	4328.34	5451	177.93	2.55	63813.3	195.27
LSa	3	5	139.38	186.36	6192.93	6888	220.53	2.22	61883.1	72.39
LSa	3	6	172.38	206.61	5663.55	15724	299.01	2.52	69753.3	65.19
LSa	4	1	79.8	258.24	6156.19	6590	143.4	0.12	48248.1	191.04
LSa	4	2	167.88	362.43	5790.42	7019	417.36	4.41	57358.8	105.66
LSa	4	3	103.14	207.51	4913.43	21719	378.6	0.99	53649.6	63.63
LSa	4	4	134.82	470.58	5378.2	6042	1642.8	9.21	50355.3	454.26
LSa	4	5	143.55	184.11	4377.68	4739	247.38	3.18	65984.7	76.65
LSa	4	6	143.82	280.89	6064.59	22287	1106.97	4.92	56575.2	123.33
ADf	1	1	120.84	12830.01	3996.24	30671	1977.48	2351.07	18701.82	7079.1
ADf	2	1	109.95	13121.73	4308.27	26579	1909.5	2376.9	19752.9	7195.5
ADf	3	1	120.84	12830.01	3996.24	26563	1977.48	2351.07	18701.82	7079.1
ADf	4	1	109.95	13121.73	4308.27	26471	1909.5	2376.9	19752.9	7195.5

**Appendix O. Continued.**

Treatment	block	depth	KCl_P	NaOH_P	HCl_P	TKP	M1 P	M1 Al	M1 Ca	M1 Fe
							mg kg <sup>-1</sup>			
LSf	1	1	654.66	429.84	5112.96	8611	1149.06	27.57	63928.2	46.77
LSf	2	1	551.85	445.5	4982.97	8571	1129.2	33.6	68632.5	44.1
LSf	3	1	654.66	429.84	5112.96	8750	1149.06	27.57	63928.2	46.77
LSf	4	1	551.85	445.5	4982.97	8684	1129.2	33.6	68632.5	44.1
Control	1	1	2.34	25.92	0.54	29	13.2	45.06	105.21	24.81
Control	2	1	1.53	11.76	0.54	30	23.13	54.51	222.99	37.62
Control	3	1	0.54	13.59	0.54	30	8.4	38.58	111.96	22.77
Control	4	1	2.28	11.4	0.54	33	12.18	45.75	104.73	33.42

**Appendix P. Entrenched biosolids moisture,  $\rho_b$ , pH, Eh, C and N forms.**

Treatment	block	depth	moisture	$\rho_b$ , kg m <sup>-3</sup>	pH	Eh, mV	C <sub>org</sub> , %	C <sub>carbonates</sub> , %	NO <sub>3</sub> -N	NH <sub>4</sub> -N mg kg <sup>-1</sup>	TKN
ADa	1	1	0.46	367	4.8	352	23.50047	0	932	31	21228
ADa	1	2	0.54	275	4.84	274	23.43722	0	506	54	23907
ADa	1	3	0.70	217	5.64	323	25.43797	0	867	167	32433
ADa	1	4	0.58	283	4.86	350	19.66452	0	707	85	32114
ADa	1	5	0.74	170	6.83	242	23.47668	0	423	5325	27815
ADa	1	6	0.57	294	4.88	316	24.66734	0	701	2351	20932
ADa	2	1	0.49	388	4.77	323	23.09543	0	441	204	22770
ADa	2	2	0.61	257	4.78	322	24.42096	0	793	200	23873
ADa	2	3	0.64	276	5.46	283	22.26013	0	598	53	22185
ADa	2	4	0.56	261	4.48	340	24.1192	0	804	150	25895
ADa	2	5	0.73	216	6.9	202	22.25714	0	647	3318	34757
ADa	2	6	0.74	252	7.92	144	26.12748	0	0	8959	33588
ADa	3	1	0.51	252	4.94	313	21.4176	0	252	77	26239
ADa	3	2	0.57	242	4.43	342	22.55315	0	521	99	24856
ADa	3	3	0.63	161	4.48	340	22.94531	0	822	95	30415
ADa	3	4	0.50	323	4.97	312	23.96483	0	305	81	23732
ADa	3	5	0.69	167	5.67	271	24.39143	0	923	80	35901
ADa	3	6	0.71	157	6.83	244	25.67445	0	482	5587	30697
ADa	4	1	0.56	276	4.56	335	23.44162	0	775	221	24593
ADa	4	2	0.58	312	4.55	336	23.41516	0	736	155	30995
ADa	4	3	0.65	298	4.99	310	21.61231	0	1120	208	26043
ADa	4	4	0.65	201	5.85	261	17.44673	0	1105	1365	28520
ADa	4	5	0.74	189	7.58	162	24.50499	0	23	5031	26855
ADa	4	6	0.69	209	5.56	277	23.65038	0	885	1991	40142

## Appendix P. Continued.

Treatment	block	depth	moisture	$\rho_b$ , kg m <sup>-3</sup>	pH	Eh, mV	C <sub>org</sub> , %	C <sub>carbonates</sub> , %	NO <sub>3</sub> -N	NH <sub>4</sub> -N mg kg <sup>-1</sup>	TKN
LSa	1	1	0.63	286	7.71	155	13.86278	3.466382	13	4606	23384
LSa	1	2	0.67	298	11.47	-54	25.43837	1.472115	166	2159	19690
LSa	1	3	0.51	459	11.7	-66	11.59272	0	224	1694	21507
LSa	1	4	0.66	309	7.74	154	17.04362	3.714612	3	5569	25330
LSa	1	5	0.65	282	11.3	-44	22.79868	4.697438	129	1653	15034
LSa	1	6	0.67	256	11.94	-79	26.23978	2.852063	166	1402	28006
LSa	2	1	0.44	388	7.26	180	15.27413	3.167886	484	35	17993
LSa	2	2	0.61	405	7.74	154	22.79917	5.394056	4	4675	25654
LSa	2	3	0.67	369	7.88	146	22.15309	7.609625	1	6109	13634
LSa	2	4	0.42	487	7.41	172	18.15864	2.599592	71	178	15070
LSa	2	5	0.63	385	8.04	137	25.67272	3.434884	5	3447	41870
LSa	2	6	0.64	422	9.18	74	28.84222	1.896288	35	3403	21725
LSa	3	1	0.59	252	7.59	162	18.86755	1.276966	63	993	21598
LSa	3	2	0.61	300	10.5	0	27.70845	2.011735	193	1266	29335
LSa	3	3	0.62	468	9.96	30	18.16818	0	119	6040	17850
LSa	3	4	0.57	308	7.6	161	27.13301	3.499921	2	4951	20356
LSa	3	5	0.65	303	11.21	137	27.25688	2.524872	52	1530	22598
LSa	3	6	0.66	333	9.92	33	29.93502	0	122	1439	18364
LSa	4	1	0.54	305	7.79	151	20.69883	7.282116	30	624	17853
LSa	4	2	0.63	330	7.93	143	30.42573	0.265741	17	3721	27170
LSa	4	3	0.64	245	8.11	133	20.52867	0	10	8776	36657
LSa	4	4	0.59	305	7.84	148	26.41085	4.222084	1	2663	24127
LSa	4	5	0.67	272	11.18	-37	31.65099	0	37	2547	20881
LSa	4	6	0.63	372	9.31	67	31.77489	0	74	1830	43761



## Appendix P. Continued.

Treatment	block	depth	moisture	$\rho_b$ , kg m <sup>-3</sup>	pH	Eh, mV	C <sub>org</sub> , %	C <sub>carbonates</sub> , %	NO <sub>3</sub> -N mg kg <sup>-1</sup>	NH <sub>4</sub> -N	TKN
ADf	1	1	0.71	179	8.07	-58	30.66819	0	1	9928	52188
ADf	2	1	0.72	187	8.15	-80	30.78105	0	1	10002	53684
ADf	3	1	0.70	193	8.1	2	30.66819	0	2	9965	53125
ADf	4	1	0.71	184	8.12	-37	30.78105	0	1	9921	53235
LSf	1	1	0.65	287	12.47	-146	33.03816	0	31	843	43611
LSf	2	1	0.63	269	12.46	-108	33.03816	0	26	876	44762
LSf	3	1	0.65	305	12.49	-125	33.03816	0	29	815	44688
LSf	4	1	0.66	273	12.53	-112	33.03816	0	28	847	44474
Control	1	1	0.10	1254	7.41	340	0.0513	0	1	1	4
Control	2	1	0.10	1265	7.28	350	0.032822	0	1	1	2
Control	3	1	0.11	1246	7.17	398	0.0513	0	1	1	2
Control	4	1	0.11	1257	7.42	401	0.032822	0	1	1	2

**Appendix Q. Entrenched biosolids N<sub>2</sub>O, CH<sub>4</sub> and CO<sub>2</sub> production.**

Treatment	block	depth	N <sub>2</sub> O	CH <sub>4</sub> mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub>
ADa	1	1	5.790074	-0.01695	2436.814
ADa	1	2	5.040788	0.277983	4323.476
ADa	1	3	8.283755	0.023401	1385.233
ADa	1	4	13.45902	0.177006	1611.912
ADa	1	5	243.8758	0.195405	2617.322
ADa	1	6	14.21437	0.17798	3229.218
ADa	2	1	10.29115	0.149436	2405.174
ADa	2	2	0.088818	1.75056	5002.883
ADa	2	3	5.723446	0.010003	847.0033
ADa	2	4	9.257212	0.048541	1633.586
ADa	2	5	377.3878	0.071193	2235.344
ADa	2	6	23.00185	0.054225	4447.261
ADa	3	1	5.818036	0.116548	1035.336
ADa	3	2	182.2524	-0.00286	2793.363
ADa	3	3	300.6928	-0.03075	2133.101
ADa	3	4	70.11655	0.171805	2471.203
ADa	3	5	6.360727	0.065069	1985.533
ADa	3	6	2.370471	2.060741	2778.104
ADa	4	1	3.559791	0.066716	1754.791
ADa	4	2	0.947953	0.152282	1192.475
ADa	4	3	8.14938	-0.03156	976.0693
ADa	4	4	3.288964	0.129937	1140.047
ADa	4	5	1.396614	0.582971	4226.806
ADa	4	6	11.90117	-0.06628	1961.838
LSa	1	1	1.003716	-0.09171	97.68488
LSa	1	2	1.286846	-0.03279	20.29961
LSa	1	3	1.673512	-0.08091	55.71077
LSa	1	4	11.86162	0.023592	6483.493
LSa	1	5	1.171085	0.104622	142.0517
LSa	1	6	1.165493	-0.07732	77.26904
LSa	2	1	0.485711	-0.12741	1432.308
LSa	2	2	3.101862	-0.00842	76.7897
LSa	2	3	0.769639	-0.06012	30.81711
LSa	2	4	3.966749	0.076927	7204.63
LSa	2	5	3.684259	-0.08317	82.36601
LSa	2	6	4.401909	-0.03129	58.80251
LSa	3	1	2.611419	-0.37211	5284.714

## Appendix Q. Continued.

Treatment	block	depth	N <sub>2</sub> O	CH <sub>4</sub> mg m <sup>-2</sup> h <sup>-1</sup>	CO <sub>2</sub>
LSa	3	2	4.088901	-0.09469	58.72262
LSa	3	3	3.613397	0.048749	35.02331
LSa	3	4	3.512496	-0.11052	4392.493
LSa	3	5	0.644452	-0.07734	60.89961
LSa	3	6	1.02265	-0.00057	16.56477
LSa	4	1	5.30051	-0.08704	125.9259
LSa	4	2	1.219339	-0.18235	-29.0923
LSa	4	3	0.586612	0.091041	20.48736
LSa	4	4	2.583937	-0.06425	3899.813
LSa	4	5	0.627116	-0.09	57.18474
LSa	4	6	0.770678	-0.06027	173.8718
ADf	1	1	0	37.99125	2796.788
ADf	2	1	0.070843	29.6014	2840.029
ADf	3	1	0	33.91105	2827.035
ADf	4	1	0	35.88999	2795.474
LSf	1	1	0.049832	-0.02656	62.45985
LSf	2	1	0.048554	-0.1654	124.9037
LSf	3	1	0.05103	-0.17494	14.30227
LSf	4	1	0	-0.07394	32.10572
Control	1	1	0.110309	-0.09022	47.66825
Control	2	1	0.011165	-0.19584	93.93244
Control	3	1	0.001898	-0.23521	48.84663
Control	4	1	0.02235	-0.09137	42.35558