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NUTRIENT MOBILITY FROM BIOSOLIDS
LAND APPLICATION SITES

by

Mai Anh Vu Tran

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

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2008

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ABSTRACT

Nutrient Mobility from Biosolids Land Application Sites

by

Mai Anh Vu Tran, Doctor of Philosophy

Utah State University, 2008

Major Professor: Dr. Michael J. McFarland
Department: Civil and Environmental Engineering

Three types of biosolids (lime-stabilized, aerobically digested, and anaerobically digested biosolids) were applied on 0.13-ha test plots on disturbed rangelands in Western Utah at rates of up to twenty times (20X) the estimated N-based agronomic rate. Soil samples at depths up to 1.5 m were collected and analyzed for nitrogen, phosphorus, regulated metals, pH, and electrical conductivity for up to two years after biosolids application.

$\text{NH}_4\text{-N}$ at the soil surface (0.2 m) was primarily lost through ammonia volatilization and nitrification. This observation was consistent with reported increases in nitrate ($\text{NO}_3\text{-N}$) concentrations found within the soil surface on the biosolids-amended sites. A nitrogen mass balance on the surface soil control volume indicated that the nitrogen residual field measurements were significantly higher than the nitrogen level estimated by accounting for nitrogen inputs (biosolids) and outputs (vegetative yield, nitrogen volatilization and nitrate leaching). Biosolids land application led to increases in vegetative growth and dry matter yield when compared to vegetation grown on control

plots. Based on the Root Zone Water Quality Model (RZWQM), the model predicted NH_4 and NO_3 storage values at biosolids-amended sites were significantly different from the field data, which suggests that the model default and limited measured values were inappropriate for a non-irrigated rangeland landscape.

The majority of total P and plant available P accumulation was found to occur primarily within the soil surface (0.2 m). Phosphorus soil residual measurements were higher than phosphorus accumulation based on a phosphorus mass balance at soil surface. The phosphorus leachability to ground water at the biosolids-amended treatment sites was low based on the molar ratio of ($[\text{P}]/([\text{Al}]+[\text{Fe}])$) and the potential formation of calcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$). Aerobically digested biosolids appeared to be the optimal biosolids type with regard to minimizing the adverse environmental effects of phosphorus based on the Phosphorus Site Index (PSI).

Regulated metal concentrations (As, Cd, Cu, Pb, Mo, Ni, Se, and Zn) were well below the cumulative pollutant loading limits for biosolids-amended soils. Finally, nutrients as well as regulated heavy metals associated with biosolids land application to disturbed rangelands do not pose any significant threat to the environment.

(147 pages)

To my parents,

Minh B. Vu and Cuc T. Tran

My sister,

Ngoc Anh Vu Tran

For their love and sacrifice for me to finish this PhD dissertation

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Mai Anh Vu Tran

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CHAPTER I

INTRODUCTION

Definitions of Biosolids

Residual solids or sewage sludge is produced through the processing of wastewater at municipal wastewater treatment plants. The higher the water-quality standards for municipal wastewater effluents, the more sewage sludge is produced. Consequently, cost-effective means of reusing or disposing of sewage sludge in an environmentally safe and acceptable manner are needed (McFarland, 2001). In order to reduce the potential environmental and human health risks from the beneficial use and disposal of sewage sludge, Section 405 of the Clean Water Act (CWA) was amended in 1987. With this amendment, numeric limits and management practices to protect public health and the environment from adverse effects of pollutants found in sewage sludge were promulgated by the U.S. Environmental Protection Agency (USEPA). The final 40 CFR Part 503 Rule (Standards for the Use or Disposal of Sewage Sludge) was released by the USEPA on February 19, 2003.

The term *biosolids* was adopted by the USEPA in recognition of the plant nutritional and soil conditioning value of sewage sludges that meet the regulatory requirements specified in the 40 CFR Part 503 Rule (McFarland, 2001). According to the USEPA (2000), biosolids are “primarily organic materials produced during wastewater treatment which may be put to beneficial use”. Biosolids are also defined as “a slow release nitrogen fertilizer with low concentrations of other plant nutrients” (USEPA, 2007). Thus, the outstanding difference between sewage sludge and biosolids is that

biosolids must meet specific quality parameters as codified under the 40 CFR Part 503 rule (USEPA, 2007).

Approximately 3,300 of the largest wastewater treatment facilities out of 16,583 produce more than 92% of the total biosolids in the United States (U.S.) (NEBRA, 2007). As reported by NEBRA (2007), 7,180,000 dry U.S. tons of biosolids were beneficially used across the United States (US) in 2004. Of that, 55% of the beneficially reused biosolids were applied to soils for agricultural purposes or land restoration while municipal solid waste (MSW) landfills or incineration facilities were responsible for the remaining 45% (NEBRA, 2007). According to National Biosolids Partnership (NBP, 2006), 63% of the total biosolids generated (~ 7.1 million tons) were recycled in 2000. By 2010, it is anticipated that 70% of the total biosolids generated will be recycled (NBP, 2006).

Classification of Biosolids

There are two types of biosolids based on the pathogen characteristics. Only biosolids that meet the Class A or Class B category may be legally land applied (McFarland, 2001; USEPA, 2000). Class A biosolids have no detectable pathogens (fecal coliforms or *Salmonella* sp.) and can be applied safely to lawns, home gardens or other public contact sites. To achieve Class A biosolids, wastewater treatment plants can choose one of six alternatives listed in the 40 CFR Part 503 Rule (McFarland, 2001). With Class B biosolids, the concentration of pathogens is reduced sufficiently to protect human health and the environment. Wastewater treatment plants may choose one of three alternatives to meet Class B pathogen-reduction criteria.

In addition to Class A and Class B biosolids, there is a special category of biosolids called exceptional-quality (EQ) biosolids. For biosolids to be considered EQ material, biosolids must meet three requirements including: 1) the pollutant concentration limits (mg/kg) may not be exceeded, 2) one of the Class A pathogen-reduction alternatives must be met, and 3) one of the first eight vector attraction reduction methods must be employed (McFarland, 2001). Exceptional-quality (EQ) biosolids are not subject to management practices or land application requirements listed in 40 CFR Part 503 Rule and may be land applied as free as any commercial fertilizer (McFarland, 2001).

Sludge Processing

It should be noted that sludge becomes biosolids as it meets the requirement in the 40 CFR Part 503 Rule for land application or surface disposal. There are typically four major sludge processing operations at wastewater treatment plants including a) thickening, b) stabilization, c) conditioning, and d) dewatering. Thickening is a process that removes water from sludge generated at wastewater treatment plants. A significant volume reduction is achieved after the thickening process, which also reduces both capital and operational costs for the subsequent biosolids-processing steps (McFarland, 2001). Sludge thickening is effectively achieved by a number of physical means such as gravity thickening, flotation thickening, centrifugal thickening, gravity belt thickening, and rotary-drum thickening.

Stabilization is typically the next processing operation after the thickening process. Stabilization attempts to accomplish a number of objectives including a) reduction or elimination of vector attraction, b) reduction of pathogen concentrations, c)

elimination of offensive odors, and d) reduction or elimination of the potential for putrefaction (McFarland, 2001). Stabilization is achieved by the following methods including a) anaerobic digestion, b) aerobic digestion, c) lime treatment, d) chlorine oxidation, and e) composting. In most cases, stabilization results in sludge volume reduction. However, for some stabilization methods, e.g., lime stabilization, there is an actual increase in sludge volume resulting from the sludge stabilization process.

Conditioning is a process that involves chemical and/or physical treatment of sludge prior to the dewatering process. Chemical conditioning typically increases the sludge particle size with the formation of large aggregates from small particles. Water removal from sludge is enhanced and solids capture is improved by the conditioning process (McFarland, 2001; USEPA, 1983).

The dewatering process involves an overall sludge volume reduction. After dewatering, sludge is no longer fluid and must be handled/transported as a solid (McFarland, 2001; USEPA, 1983).

Land Application of Biosolids

Biosolids are effective soil conditioners and a low cost source of plant nutrients. Managing biosolids is one of the most expensive activities of wastewater treatment plants. For example, because of the Ocean Ban Act of 1992, sludge discharge to oceans is now illegal. Similarly, the difficulty in siting monofills (biosolids only landfills) and the reluctance of municipalities in co-disposing of biosolids within municipal solid waste (MSW) landfills makes surface disposal politically and economically difficult. Incineration of biosolids is a technically feasible option but air quality concerns make this

publicly unacceptable in many areas. Therefore, beneficial use of biosolids through land application represents a technically feasible and socially acceptable option for managing biosolids (McFarland, 2001; USEPA, 2000).

Biosolids land application refers to the application of any form of bulk or bagged biosolids to land for beneficial use. Biosolids may be applied to agricultural land for food production, to pasture and rangelands or to disturbed lands. These biosolids management practices are considered as beneficial uses (McFarland, 2001; USEPA, 2000). In order to legally apply biosolids to land, any biosolids applier must meet six requirements including a) general requirements, b) pollutant limits, c) management practices, d) operational standards covering pathogen and vector attraction reduction requirements, e) recordkeeping requirements, and f) reporting requirements.

It should be noted that only nine heavy metals (As, Cd, Cu, Pb, Hg, Mo, Ni, Se, and Zn) are currently regulated for biosolids land application. These heavy metals are regulated with concentration limits and loading rate limits. Concentration limits refer to limits of heavy metal concentration in biosolids while loading rate limits the rate at which biosolids can be applied to land. Concentration limits are further categorized into two types including ceiling concentration limits and pollutant concentration limits (Table 1). Ceiling concentration limits decide whether biosolids are qualified for land application whereas pollutant concentration limits define biosolids that are exempted from meeting pollutant loading rate limits (McFarland, 2001; USEPA, 1995). The metal limits in soils receiving biosolids land application are represented by the cumulative pollutant loading rate and annual pollutant loading rate (Table 2).

Table 1. Concentration limits for biosolids applied to lands[§]

Pollutant	Ceiling concentration limits (mg/kg)^{§§}	Pollutant concentration limits[¶] (mg/kg)
Arsenic	75	41
Cadmium	85	39
Copper	4300	1500
Lead	840	300
Mercury	57	17
Molybdenum	75	NA ^{§§§}
Nickel	420	420
Selenium	100	36
Zinc	7500	2800

[§]Adapted from USEPA (1995) and McFarland (2001)

^{§§}Dry-weight basis

^{§§§}USEPA is re-examining the limit

[¶]Monthly average concentration

Table 2. Loading rate limits for land-applied biosolids[§]

Pollutant	Cumulative pollutant loading rate limits (kg/ha)	Annual pollutant loading rate limits (kg/ha)
Arsenic	41	2
Cadmium	39	1.9
Copper	1500	75
Lead	300	15
Mercury	17	0.85
Molybdenum	NA ^{§§}	NA ^{§§}
Nickel	420	21
Selenium	100	5
Zinc	2800	140

[§]Adapted from USEPA (1995) and McFarland (2001)

^{§§}USEPA is re-examining these limits

As reported by USEPA (2000), approximately 54% of wastewater treatment plants chose land application as an option for their biosolids management. Land application of biosolids steadily increased in the 1980s due to decreasing availability and increasing costs of landfill disposal methods (USEPA, 2000). In addition, biosolids

quality has been improved through the implementation of the Nationwide Pretreatment Program that requires commercial and industrial dischargers to treat or control pollutants in their wastewater before discharge to Publicly Owned Treatment Works (POTWs). The adoption of the 40 CFR Part 503 Rule led to a consistency in procedures of biosolids land application across the nation (USEPA, 2000).

Land application of biosolids has both advantages and disadvantages. Advantages of biosolids land application include improving soil structure, reduction in soil erosion, increases in vegetative growth and enhancing soil moisture infiltration. Disadvantages include uncertainty about fate and transport of non-metal pollutants, potential odors and public perception about environmental impacts of land application. Because biosolids are rich in nutrients, land application is an efficient way to recycle these nutrients onto soils. In addition, land application of biosolids has a lower capital investment than other biosolids management technologies such as surface disposal or incineration (USEPA, 2000).

Research Objectives

United States (U.S.) rangelands provide forage for wildlife and livestock production, habitat for native flora and fauna and watersheds for rural agriculture. However, because of past grazing practices, these rangelands are in a variety of conditions ranging from severely degraded landscapes to fully functional ecosystems. Poor rangeland management has led to increases in 1) soil erosion, 2) water quality deterioration, and 3) wildfire frequency and extent. The overall goal for the present study

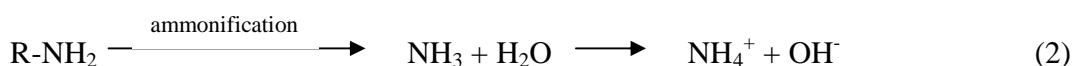
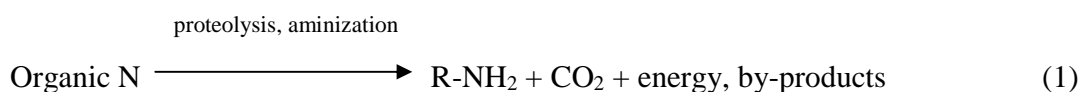
is to evaluate the fate of nitrogen (N), phosphorus (P), and metals from biosolids applied to disturbed rangelands. The following list summarizes the project's objectives.

1. Monitor the nitrate disturbed soils with and without biosolids amendments.
2. Conduct N mass balance.
3. Simulate nitrogen transport using the Root Zone Water Quality Model (RZWQM).
4. Monitor total phosphorus and bioavailable phosphorus (Olsen P).
5. Conduct P mass balance.
6. Calculate P-based agronomic rate.
7. Evaluate the effects of metals (Al, Ca, and Fe) on P leachability.
8. Evaluate P mobility using empirical correlations between P loading rate and P accumulation at soil surface.
9. Evaluate phosphorus leachability on biosolids amended sites using Universal Soil Loss Equation and Phosphorus-Site Index (PSI).
10. Develop strategies to reduce N, P availability and to minimize N, P loss from biosolids land application sites.
11. Investigate plant species at biosolids land application sites.
12. Evaluate the accumulation of regulated metals (As, Cd, Cu,, ammonia, pH and electrical conductivity (EC) in Pb, Mo, Ni, Se, and Zn) within the soil profile of sites with and without biosolids amendments.

CHAPTER II
LITERATURE REVIEW

Soil Nitrogen

Nitrate and ammonia are assumed the only forms of nitrogen that are available for plant uptake in the present crop-growing year (McFarland, 2001). Therefore, the term *mineralization* refers to the transformation of any organic N (e.g. proteins, nucleic acids, or amino sugars from microbial cell walls) to these inorganic species. The mineralization is mediated by microbial activities in soil and any organic form of N is converted into NH_4^+ . Pierzynski, Sims, and Vance (2000) summarized the N mineralization process as follows:



The mineralization of organic soil nitrogen has been described by the first-order kinetic model in which the change in mineralized N in soil respective to time was related to the initial amount of organic N (Pierzynski, Sims, and Vance, 2000).

NH_4^+ can be taken up by plants or it will be converted into nitrate (NO_3^-) through the nitrification process. Nitrification is an aerobic process mediated by microbial activity. NH_4^+ is first oxidized to nitrite (NO_2^-) by the bacterium *Nitrosomonas*. Nitrite is

then oxidized to nitrate (NO_3^-) by the bacterium *Nitrobacter*. The overall ammonium oxidation to nitrate is described as followed:



Then NO_3^- is taken up by plants or is converted to N_2 gas through denitrification. Denitrification is an anaerobic process, which is subject to reducing conditions in soils. The final product of denitrification process is nitrogen gas.



Additionally, NH_4^+ may be lost as ammonia gas through volatilization which is strongly dependent on pH and temperature of soils and some other soil properties. For example, ammonia volatilization may be a significant nitrogen-removal mechanism in alkaline soils (i.e. soils with high pH), or calcareous soils, or soils with low cation exchange capacities (CEC) and high temperature (low precipitation). The chemical mechanism that facilitates ammonia volatilization is described in Eq. 6:



An increasing pH shifts the reaction to the right and results in an increase of ammonia gas. NH_4^+ may also be immobilized by soil microorganisms or be held as exchangeable ion by soil colloids or clays (Pierzynski, Sims, and Vance, 2000). For a summary of the soil nitrogen cycle, Figure 1 illustrates the principal sources and sinks of nitrogen in soil.

Both organic and inorganic nitrogen are added to soils during biosolids land application. Then NH_4^+ may be converted to nitrate (NO_3^-) through nitrification or NH_4^+ may be lost as ammonia gas (NH_3) (Sierra, Fontaine, and Desfontainers, 2001; Shi et al., 1999; Robinson and Polglase, 2000). Ammonia gas is considered a greenhouse gas since

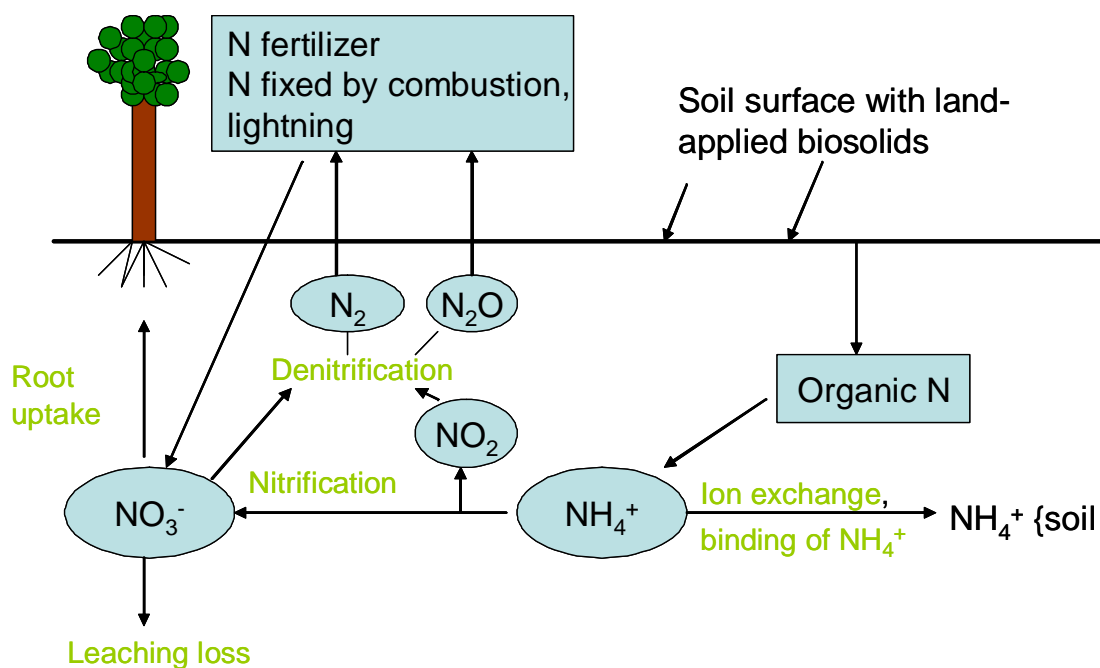


Figure 1. Nitrogen sink and pathways in soil. Adapted from Manahan (2001)

it forms transport aerosols in the atmosphere (Mendoza, Assadian, and Lindemann, 2006). Wang, Kimberley, and Schlegelmilch (2003) reported that mineralization of organic N during biosolids land application is dependent on temperature and soil type, which was demonstrated by their experiments at two different temperatures (10°C and 20°C) and two soil types in New Zealand (volcanic soil and brown soil). A higher rate of N mineralization was reported at higher temperatures. Mineralization of N also varies between different types of biosolids applied to soils (Parker and Sommers, 1983). For example, aerobically digested biosolids yielded higher N mineralization (32.1%) than anaerobically digested biosolids (15.2%) as they were applied to forest soils (Wang Kimberley, and Schlegelmilch, 2003). There is concern that excess N from biosolids land application with application rates significantly higher than estimated agronomic rate may result in excess nitrate, which can cause an elevation of NO_3^- in ground water due to its

high leachability (Brady and Weil, 1996). Hence, the limiting factor in a biosolids land application is excess N leaching (Cogger et al., 2001).

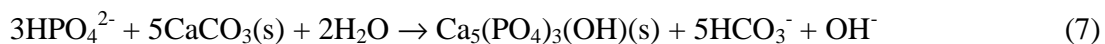
In addition to temperature, pH values of soils also affect the mineralization rate of N in biosolids-amended soils (Garau, Felipo, and Ruiz de Villa, 1986). At extreme pH values (>10 or <4), microbial activity is inhibited and N mineralization rates are reduced. Beyond mineralization rates, pH also affects the abiotic mechanisms such as volatilization.

Soil Phosphorus

Like nitrogen, phosphorus must be in inorganic forms for plant uptake. The concentration of total P in soil varies from 50 to 1500 mg/kg, of which 70% is in inorganic form in mineral soils (Pierzynski, Sims, and Vance, 2000). Soil inorganic P is mainly transformed by the fixation of soluble P forms through adsorption and precipitation reactions and by the solubilization of P through desorption reactions and mineral dissolution (Pierzynski, Sims, and Vance, 2000). The phosphorus source in soil is from biosolids, commercial fertilizers, animal manure, plant residues, industrial and domestic waste, or native forms of phosphorus in soils, which is usually organic P.

Organic P will be mineralized by microorganisms to inorganic P, which exists in the environment under various forms with different oxidation states. However, orthophosphate (H_2PO_4^- and HPO_4^{2-}) is the predominant phosphorus species in soils and it is usually available for plant uptake at neutral pH. These soluble orthophosphates tend to combine with metal ions (e.g., Ca^{2+} , Fe^{3+} , and Al^{3+}) to form phosphate compounds. For example, in acidic soils, orthophosphate is sorbed or precipitated by Al^{3+} and Fe^{3+} while

in alkaline soil, orthophosphate tends to react with CaCO_3 to form relatively insoluble hydroxyapatite as described in Eq. 7:



Conversely, immobilization is a process in which metal phosphates release soluble orthophosphate which is then converted back to organic P by microbial activities. Both mineralization and immobilization are depicted in Figure 2.

Calcium phosphates are currently the most soluble or plant-available forms of P that are found in soil. The other major forms including iron and aluminum phosphates are insoluble and unavailable for plant uptake. However, as calcium phosphates are taken up by plants, replenishment of phosphorus occurs due to the shift of the equilibria with absorbed phosphorus and phosphorus minerals.

Phosphorus is believed to significantly contribute to eutrophication in surface waters (Manahan, 2001; Pierzynski, Sims, and Vance, 2000). Eutrophication is caused by excess nutrients in surface waters, which results in excessive biomass growth. When they die, the increased biomass will deplete dissolved oxygen leading to fish kills (Pierzynski, Sims, and Vance, 2000). Eutrophication not only causes ecological damages but also increases economic costs for surface water maintenance for recreational and navigational purposes. However, it is important that both excess N and P in surface waters are minimized to control eutrophication. The ratio of N to P in the water body is an important indicator to determine which nutrient is limiting the eutrophication (Pierzynski, Sims, and Vance, 2000). The overall soil P cycle is illustrated in Figure 3.

Eutrophication of surface waters such as the Great Lakes and the Everglades has been of particular interest because of they have received long-term P application from

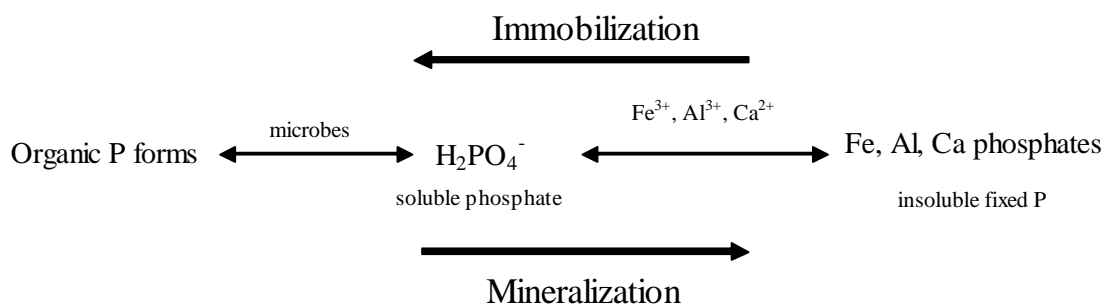


Figure 2. Phosphorus transformation in soil.

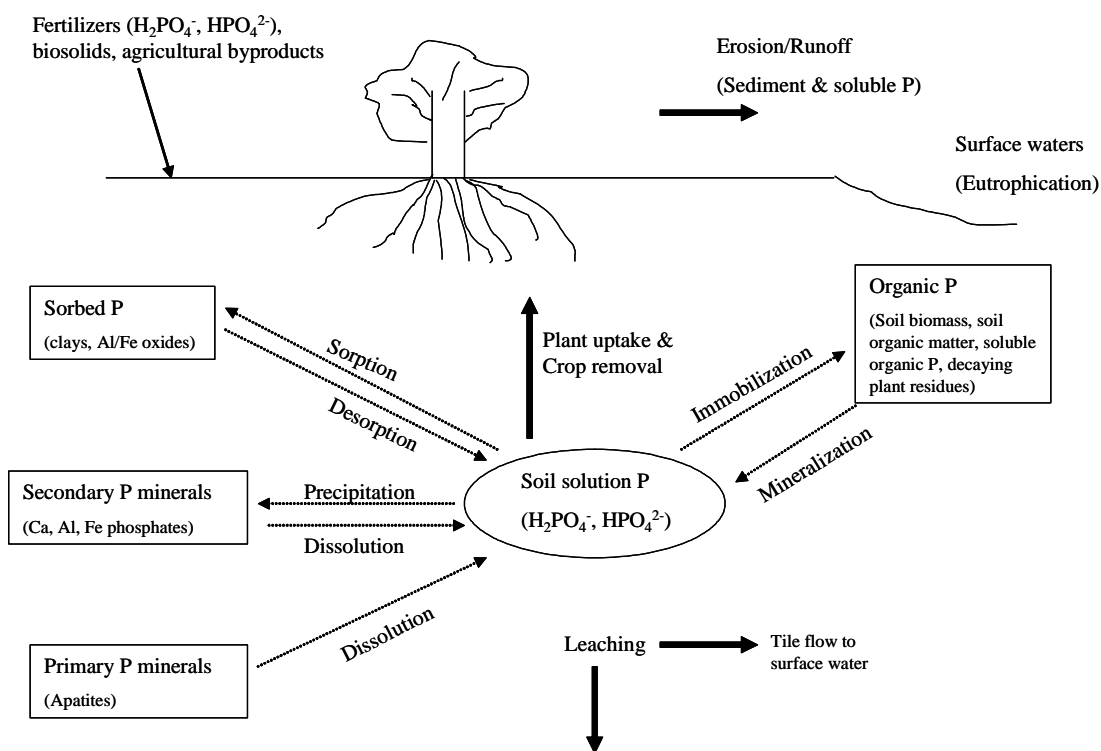


Figure 3. Soil P cycle. Adapted from Pierzynski, Sims, and Vance (2000)

fertilizers, manures, and biosolids (Daniel, Sharpley, and Lemunyon, 1998; Maguire, Sims, and Coale, 2000). In addition, excess P from biosolids land application can be lost through soil erosion or runoff, which contributes to the growth of *Pfiesteria* spp., which

is believed to cause fish kills and human health problems (Burkholder and Glasgow, 1997).

The total P concentration in biosolids is typically 10 to 20 g per kg (USEPA, 1995; Peters and Basta, 1996). A goal of wastewater treatment plants is to reduce P concentrations in their effluents to limit eutrophication (Seyhan and Erdinçler, 2003; Hogan, McHugh, and Morton, 2001). Biosolids land application typically is limited by the rate at which biosolids N provides N requirement for crops (Elliott, Brandt, and O'Connor, 2005). However, given the typical nutrient quantities found in biosolids, it is difficult to meet both the N-based and P-based agronomic rates at the same time. Although P is an important nutrient for crops, excess P (dissolved and particulate P) can lead to eutrophication in surface waters (Parry, 1998; Cann, 1995). More intensive P managements for biosolids land application, manure application or commercial fertilizer usage have been implemented across the nation (Maguire, Sims, and Coale, 2000) to address the concern of excess P from these practices. Ippolito, Barbarick, and Norvell (2007) proposed that the best management for biosolids land application should be based on P loading. However, P has a variety of forms depending on biosolids treatment process. For example, extractable soil P and runoff dissolved reactive P significantly increased in soil amended with biosolids that were produced by biological removal process (Penn and Sims, 2002). In addition, bioavailability of biosolids P is dependent on several factors, e.g., addition of Fe, Al, or Ca in treatment processes can reduce P solubility in biosolids (Lu and O'Connor, 2001).

Despite the potential environmental and economic benefits associated with biosolids land application, questions still remain regarding the fate and transport of

biosolids constituents particularly when biosolids are land applied at rates significantly greater than the agronomic rate. Fitzpatrick et al. (2004) stated that the leaching of total phosphorus from two sites in South Dakota increased from 46 to 92-cm depth not because of an increase in biosolids application rate but because of changes in phosphorus mobility and other soil properties.

Soil Trace Elements

Trace elements in soil originate from both natural and anthropogenic sources (Pierzynski, Sims, and Vance, 2000). For a long time, soil contamination has been caused by the mining and smelting of trace elements. Emissions of trace elements from motor vehicles partly contribute to trace element build-up in soil. Smoke containing trace elements is emitted into the atmosphere and precipitation then cycles trace elements back to the soil. Fine particles from coal combustion are another source of trace elements in soil as they are released into the atmosphere and deposited into soil by precipitation. Additionally, land application of biosolids for beneficial use or disposal strategy can result in trace element accumulation in soil. Similarly, soil may be enriched with trace elements from utilization of fertilizers, pesticides or manures for agricultural operations.

Although some trace elements are necessary for the growth of humans, animals, organisms, and plants, excess trace elements can cause a number of adverse effects. Human and animals are mainly exposed to trace elements in soil through the food chain route and through direct ingestion of soil particles (Pierzynski, Sims, and Vance, 2000). Plants are adversely affected by trace elements through phytotoxicity which is defined as reduced yields or death of plants (Pierzynski, Sims, and Vance, 2000). Trace element

enrichment in aquatic environments is primarily from soil erosion, which leads to reduction of the diversity, productivity, and density of aquatic organisms (Pierzynski, Sims, and Vance, 2000).

A general cycle of trace elements in soil is described in Fig. 4. Plant uptake of trace elements occurs from soil solution. The fate and transport of trace elements can be highly affected by redox reactions which are of importance for some trace elements such as As, Cr, Hg, Mn, and Se (Pierzynski, Sims, and Vance, 2000). Volatilization is only important for some trace elements including Hg, As, and Se.

Bioavailability of trace elements is an important key to predict the fraction of the total trace element concentrations that is available for plant uptake. Moreover, plants usually uptake the soluble species of trace elements in soil solution, therefore trace element bioavailability is related the concentration and speciation of trace elements in soil solution (Pierzynski, Sims, and Vance, 2000). In addition, soil pH influences the bioavailability of trace elements. For example, bioavailability of cationic metals increases at decreasing pH whereas that of oxyanions is more variable.

Biosolids application leads to a number of metals applied to soil although metal concentrations in biosolids are regulated by the 40 CFR Part 503 rule before land application (McBride, 1995; McFarland, 2001). Bioavailable forms of metals may be toxic for crops and microbes (Sloan et al., 1997). For example, cadmium (Cd) and zinc (Zn) in biosolids were found to have the highest plant availability as well as high accumulation coefficients which increased their concentrations in plants in sandy loam soil at pH 6.5-7.2 (Seyhan and Erdinçler, 2003; Sloan et al., 1997; Davis and Stark, 1980). The plant availability of nickel (Ni), copper (Cu), chromium (Cr), and lead (Pb)

decreases in the respective order. The plant availability of Cd and Zn is especially enhanced with added organic matter (Almas and Singh, 2001). However, if biosolids completely decayed, it would be unlikely that biosolids-derived metals in soil solution totally became plant-available (Hurley, 1980). Additionally, plant uptake and leaching of heavy metal in biosolids-amended soils may occur rapidly due to organic matter decomposition, which may result in phytotoxic effects, ground water contamination, and even metal transfer into the food chain (Beckett and Davis, 1978). These effects are more likely long-term since the breakdown of organic matter from biosolids application is relatively slow (Sloan, Dowdy, and Dolan, 1998).

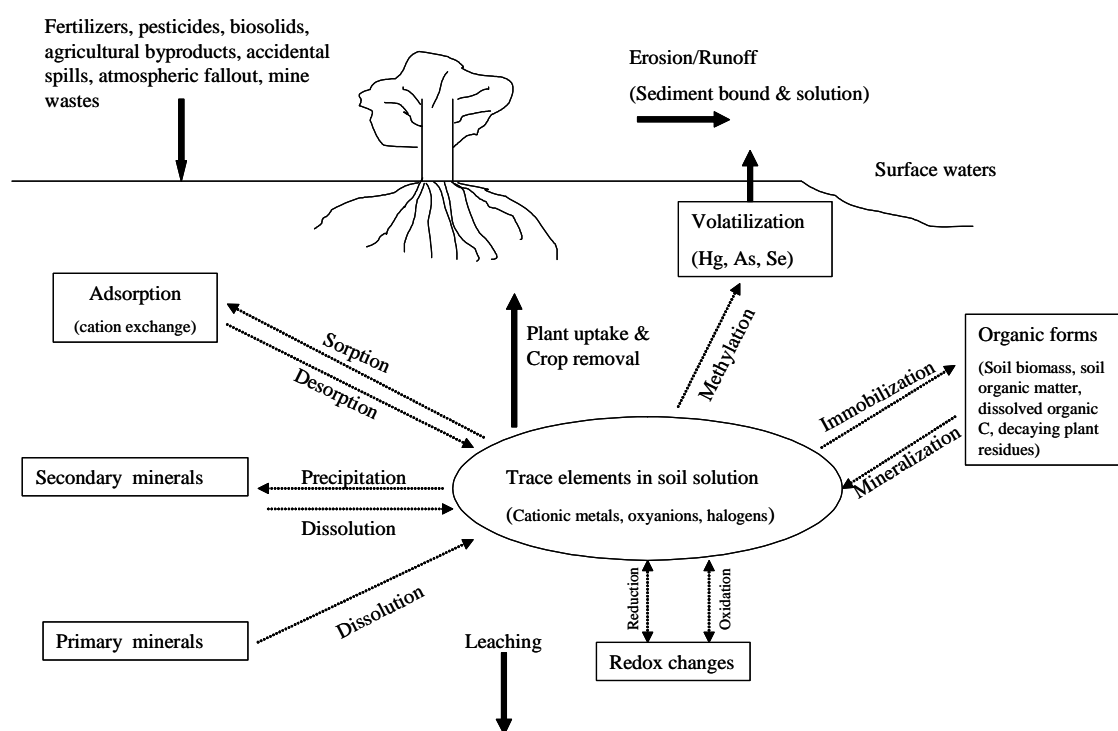


Figure 4. Soil trace element cycle. Adapted from Pierzynski, Sims, and Vance (2000)

Solubility and phytoavailability of trace metals may be reduced because of some favorable properties of biosolids (e.g., high pH) and significant amounts of sorbents (e.g., organic matter) (Basta, Ryan, and Chaney, 2005). For example, previous researchers (McCalla, Peterson, and Lue-Hing, 1977; Sommers, Nelson, and Yost, 1976) reported that biosolids contained up to 50% natural organic matter (NOM) by weight and up to 50% inorganic mineral forms by weight (e.g. silicates, phosphates, carbonates, and iron (Fe), manganese (Mn), and aluminum (Al) oxides). Basta, Ryan, and Chaney (2005) also stated that both sorption capacity and properties of both soil and biosolids would affect metal availability. Cu, Pb, Ni, and Zn were reported to be strongly adsorbed in a variety of soils (Buchter et al., 1998).

Previous researchers (Fresquez et al., 1991; Pierce et al., 1998) demonstrated that arid rangeland production was improved due to organic matter and trace metal addition from biosolids land application as compared against the unamended soil. For example, production and quality of native grass species in Colorado rangelands increased because of one-time biosolids application at variety of biosolids loading rates (Pierce et al., 1998).

CHAPTER III

MATERIAL AND METHODS

Study Site

The biosolids field study site is located in western Utah. The elevation of the site is 1300 to 1800 m. The average annual precipitation is 150 to 200 mm, the mean annual air temperature is 7 to 10⁰C, and the average frost-free period is 120 to 160 days (USDA, 2000). Permeability is moderately rapid in this soil. Available water capacity is moderate (125 to 165 mm). The content of organic matter in the surface layer is 0.5 to 1.0 percent. Runoff is slow, and the hazard of water erosion is slight. The hazard of wind erosion is moderate (USDA, 2000).

Soil Characterization

The rangeland soil is fine sandy loam with 0 to 5 percent slopes, which is deep and well-drained soil on lake terraces and fan remnants. The rangeland formed in eolian material, lacustrine sediments and alluvium derived from mixed rock sources (USDA, 2000). The present vegetation in most areas is cheatgrass, hornseed buttercup, and mouse barley (USDA, 2000). The background soil chemistry of the study site is given in Table 3. The soil replicates were taken in September 2004 prior to biosolids land application.

Biosolids Land Application

Lime-stabilized, aerobically digested, and anaerobically digested biosolids were used in this study, which came from Tooele City Wastewater Treatment Plant (WWTP),

the Snyderville Basin Wastewater Treatment Plant (WWTP), and the Central Valley Wastewater Treatment Plant (WWTP), respectively. The biosolids compositions are displayed in Table 4. In addition, the concentrations of nine heavy metals in biosolids which are currently regulated under the 40 CFR Part 503 Rule are shown in Table 5.

The biosolids were land applied on 0.13-ha test plots separated by buffer strips on private rangeland located in western Utah at various application rates. Lime-stabilized and aerobically digested biosolids were land applied in December 2004 while anaerobically digested biosolids were land applied in April 2005. The biosolids application rate was determined as the N-based agronomic rate which met the crop N requirement.

Table 3. Soil background chemistry

Sample ID	Depth bgs (m)	pH	Total N (%)	NO ₃ -N (mg/kg)	NH ₄ -N (mg/kg)	Bioavailable P (mg/kg)	EC (dS/m)	SAR
A1	0.2	7.90	0.04	26.7	6.86	16.80	10.2	6.39
A2	0.6	7.95	0.03	107.0	9.00	7.40	29.1	15.80
A3	0.9	7.86	0.03	135.0	6.33	16.20	43.3	40.90
A4	1.2	7.76	0.05	146.0	9.44	5.00	44.6	54.40
A5	1.5	7.85	0.94	146.0	10.40	5.10	39.0	53.90
B1	0.2	8.26	0.07	21.8	22.40	11.80	14.9	168.00
B2	0.6	8.06	0.02	67.6	56.50	7.70	36.3	27.80
B3	0.9	7.96	0.02	80.1	6.81	0.01	38.8	58.10
B4	1.2	7.76	0.02	111.0	7.45	22.00	49.3	39.50
B5	1.5	7.75	0.04	156.0	10.00	51.00	51.8	40.50
C1	0.2	8.26	0.04	10.4	7.78	6.90	4.9	210.50
C2	0.6	8.59	0.01	24.7	4.15	2.20	20.0	18.70
C3	0.9	8.15	0.01	63.2	6.85	1.70	34.8	39.00
C4	1.2	7.99	0.01	74.3	6.70	2.60	37.0	47.30
C5	1.5	7.90	0.01	92.6	6.07	5.10	39.5	44.70

Bgs = Below ground surface

EC = Electrical Conductivity

SAR = Sodium Adsorption Ratio

Table 4. Summary of biosolids compositions

Type of biosolids	Moisture (%)	Total N (%)	NO ₃ -N (mg/kg)	NH ₄ -N (mg/kg)	Total P (mg/kg)
Lime stabilized	82.5	0.89	1.22	1175	4900
Aerobically digested	6.9	5.41	1.71	2135	48100
Anaerobically digested	80.2	5.85	13.4	12500	25000

Table 5. Concentrations of regulated heavy metals (mg/kg) in three types of biosolids

Pollutant	Type of biosolids		
	Lime-stabilized	Aerobically digested	Anaerobically digested
Arsenic	<*	2	21
Cadmium	0.261	0.98	2
Copper	51	99	560.9
Lead	5	41	65.6
Mercury	0.185	1	3.2
Molybdenum	1.3	1.8	16.4
Nickel	2.8	2.1	38.5
Selenium	<*	2	21.9
Zinc	54	200	877.3

* Below detection limit

The nitrogen requirement for rangeland grasses can vary from approximately 110 kg N/ha to over 450 kg N/ha depending on the species as well as vegetative density (Johnson, 1989). Therefore, the agronomic rate (metric ton/ha) for the surface application of biosolids was determined based on the assumption that a healthy rangeland would exhibit a nitrogen demand of 170 kg N/ha (USDA, 2000). This nitrogen demand estimate was based on the assumption that a healthy rangeland would be dominated by perennial grass species (McFarland, 2001).

A control plot, which served as a treatment performance baseline, was also established and received no organic amendments. Anaerobically digested and aerobically digested biosolids were land applied on test plots at twenty times (20X), ten times (10X),

five times (5X), and one time (1X) the estimated agronomic rate. Due to low nitrogen content in lime-stabilized biosolids, an unacceptably large biosolids application rate was found to be necessary for meeting the estimated rangeland nitrogen demand. Therefore, lime-stabilized biosolids were land applied only at 10X, 5X, and 1X the estimated agronomic rate in order to avoid practical problems associated with applying a relatively thick layer of applied biosolids. Details are given in Table 6.

Soil Sampling

To facilitate the selection of random samples, each of the 0.13-ha test plots was divided into 144 sections (or test plot sections) having physical dimensions of 3 meters by 3 meters. Six subplots were randomly chosen from each test plot using the random number generator in Microsoft Excel program. It should be noted that sampling subplots in each sampling activity were not replicated. The exact boundaries of each of the 9m² test plots were established using a global positioning system (GPS), which helps providing information about biosolids application in case the land is ever sold.

Soil sampling at the lime-stabilized, aerobically digested, and anaerobically digested biosolids land application test plots was conducted in May 2006. However, in 2005, soil samples at lime-stabilized and aerobically digested biosolids test plots were collected in May while those at anaerobically digested biosolids test plots were collected in October. The control plot was always sampled along with every sampling activity. Soil samples were taken at 0.2, 0.6, 0.9, 1.2, and 1.5-m depths below the ground surface (bgs) in each of the six subplot sections. The volume of each soil sample is 0.5 liters. One (1) borehole per test plot section was drilled using standard hand augers.

Table 6. Summary of biosolids land application rates (dry basis)

Multiple of agronomic rate (metric ton/ha)	Lime-stabilized biosolids (metric ton/ha)	Aerobically digested biosolids (metric ton/ha)	Anaerobically digested biosolids (metric ton/ha)
1X	19.75	3.44	2.86
5X	98.73	17.22	14.29
10X	197.45	34.44	28.59
20X	NA	68.88	57.17

Soil Sample Analysis

The soil sample analyses were done at Utah State University Analytical Laboratories (USUAL) using procedures described in Gavlak et al. (2003). Soil pH and electrical conductivity (EC) were measured using Method S-1.00 with a soil saturated paste. Sodium adsorption ratio (SAR) was calculated from the concentrations of dissolved Ca, Mg, and Na in a soil saturation paste extract. The cation concentrations were determined via Method S-1.00 using atomic absorption spectrometry (AAS) or inductively coupled plasma emission spectrometry (ICP-AES). The method detection limit for the cations (Ca, Mg, and Na) is 0.02 mmol L⁻¹ (on a solution basis) (Gavlak et al., 2003).

The samples were analyzed for ammonium (NH₄-N) using the KCl Extraction/Exchangeable Ammonium Method (Gavlak et al., 2003). A solution of 2.0 N KCl was used and ammonium was determined by spectrophotometric technique. The method detection limit is 0.2 mg kg⁻¹. Total N was determined using the automated combustion method. Samples were combusted in an O₂ environment with an automated resistance furnace. Total N was quantified using a thermal conductivity detector. The method detection limit is 0.0003 mg/kg N. Nitrate (NO₃-N) was analyzed using KCl

Extraction/Cd-Reduction Method. A solution of 2.0 N KCl was also used. Nitrate was determined via its reduction to nitrite ($\text{NO}_2\text{-N}$) by a cadmium reactor. Then nitrate is diazotized with sulfanilamide and coupled to N-(1-Naphthyl)-ethylenediamine dihydrochlorine to form an azochromophore which could be measured spectrophotometrically (at 520 nm). The detection limit of the method is 0.5 mg kg^{-1} . Plant available P was determined using the Sodium Bicarbonate Method (Olsen Method) (Gavlak et al., 2003). The bioavailability of ortho-phosphate ($\text{PO}_4\text{-P}$) was determined using 0.5 N NaHCO_3 solution, which was adjusted to pH 8.5 (for mildly acidic soils) to alkaline pH. The method detection limit is 2 mg kg^{-1} (on a dry soil basis). Metal contents (Al, Ca, Fe, Pb, P, Mo, Na, K, Cu, Ni, As, Se, and Zn) in the samples were analyzed using Open Vessel Digestion and Dissolution Method (for acid recoverable metals), which followed closely the EPA 3050A Method (Edgell, 1988; Gavlak et al., 2003). A nitric extraction/dissolution along with heating on a hot plate was utilized. Digest analyte concentrations were determined using inductively coupled plasma atomic emission spectrometry (ICP-AES). The method detection limits are 10 mg/kg for Ca, Mg, and P and 2.5 mg/kg for Al, Cu, Fe, Mo, Pb, and Zn. The method detection limits for Cd and Ni are 1.5 and 7.5 mg/kg, respectively. The method detection limits of As and Se were not reported by the USUAL.

Biomass Sampling

To estimate the effect of land application of the lime-stabilized, aerobically digested, and anaerobically digested biosolids on vegetative growth, biomass from each of the six test plot sections as well as the control test plot were sampled. Biomass yields

were determined by collecting vegetation using a standard gas powered lawn mower. The entire 9-m² test plot sections were mowed during biomass sampling. The harvested material was collected in plastic bags and weighed on site to obtain an estimate of the plant biomass (wet mass basis). The percentage of dry matter in biomass was analyzed by Utah State University (USU) Analytical Laboratories (Gavlak et al., 2003).

Plant Identification

Plant density on the test sites that received a variety of biosolids was determined using the Line Intercept method (Bonham, 1989; Canfield, 1941). A transect was established and the plant crowns that overlapped or intercepted the tape were recorded. The total of the intercept measurements along the transect line from all individuals of each plant species was the cover percentage of that species. The total cover percentage was obtained by totaling the cover percentages for all plant species present at the study site.

The Root Zone Water Quality Model (RZWQM)

The RZWQM model is the most complete simulation program describing the fate of nitrogen in land based waste management systems from the U.S. Department of Agriculture – Agricultural Research Service. The program is available for public use with online help as well as a publication (Ahuja et al., 2000) associated with the model. The RZWQM model can predict nutrient transport (e.g., nitrogen), not only through the root zone but also up to 1.2 m depth below ground surface, in an agricultural system

depending on agricultural management practices (tillage; irrigation; pesticide application; manure and fertilizer applications).

The first version of the Root Zone Water Quality Model (RZWQM) was completed in 1992 by the U.S. Department of Agriculture – Agricultural Research Service (USDA-ARS) in response to a variety of agricultural management practices in which control of water movement and chemical transport is of importance (Ahuja et al., 2000). The RZWQM developers stated that the specific goal of the model was to establish the interactions among hydrology, plant growth, management practice and chemical fate.

The RZWQM is a one-dimensional model (i.e., vertical into soil profile) that integrates physical, chemical, and biological processes to simulate plant growth and movements of water, nutrients and pesticides through the root zone in an agricultural cropping system (Ahuja et al., 2000). The simulation is typically executed on a unit-area basis. There are a number of management practices and scenarios for the simulation, which can be chosen by users depending on their agricultural system. The management practices include methods and timing of fertilizer, manure, and pesticide application; methods and timing of water application; tillage methods; surface residue recycling; and various crop rotations (Ahuja et al., 2000).

The RZWQM model simulates rapid transport of surface-applied chemicals within soil matrix and through macropores to deeper depths. The transport of surface-applied chemicals to runoff water was formulated to specifically simulate pesticide application to the cropping system.

The RZWQM model has been calibrated, verified, and refined by several external users since 1992. The simulation by the RZWQM can be extended up to 100 years using automated execution of certain management operation respective to crop growth stage (Ahuja et al., 2000).

The RZWQM output variables that were applicable to this work were nitrate ($\text{NO}_3\text{-N}$) and ammonium ($\text{NH}_4\text{-N}$) storage in the soil below the root zone (0.2-1.2 m) after biosolids amendments. Input data for biosolids application at the test sites were treated as manure application for ammonia and as fertilizer application for nitrate. All other information relating to the test sites including soil physical and chemical properties, meteorology, and management practices could be entered into the program according to data availability.

Statistical Analysis

The experiment in this study was designed with a pseudo replication due to financial and time constraints. However, important factors that may affect the experiment results are negligible without replication design. For example, the temperature and the water content (by precipitation) were considered the same among treatments because they are close together. A pseudo replication design is a non-independent replication of an experiment due to sub-sampling on experimental units or measuring experimental units over time.

Statistical analyses in this study were executed using a “Fixed Effect Analysis of Variance with One Treatment Factor” in the Statistical Analysis System (SAS-Version 8) due to the unbalanced experimental design. The experimental design in this study was

considered unbalanced due to the unequal number of sub-treatments in each treatment as shown in Figure 5.

The null hypothesis (H_0) is that the biosolids treatment is not different from the control at 95% confidence level (p-value is 5%). The alternative hypothesis (H_a) is that the biosolids treatment is different from the control at 95% confidence level. In other words, the null hypothesis is rejected if p-value is less than 5%.

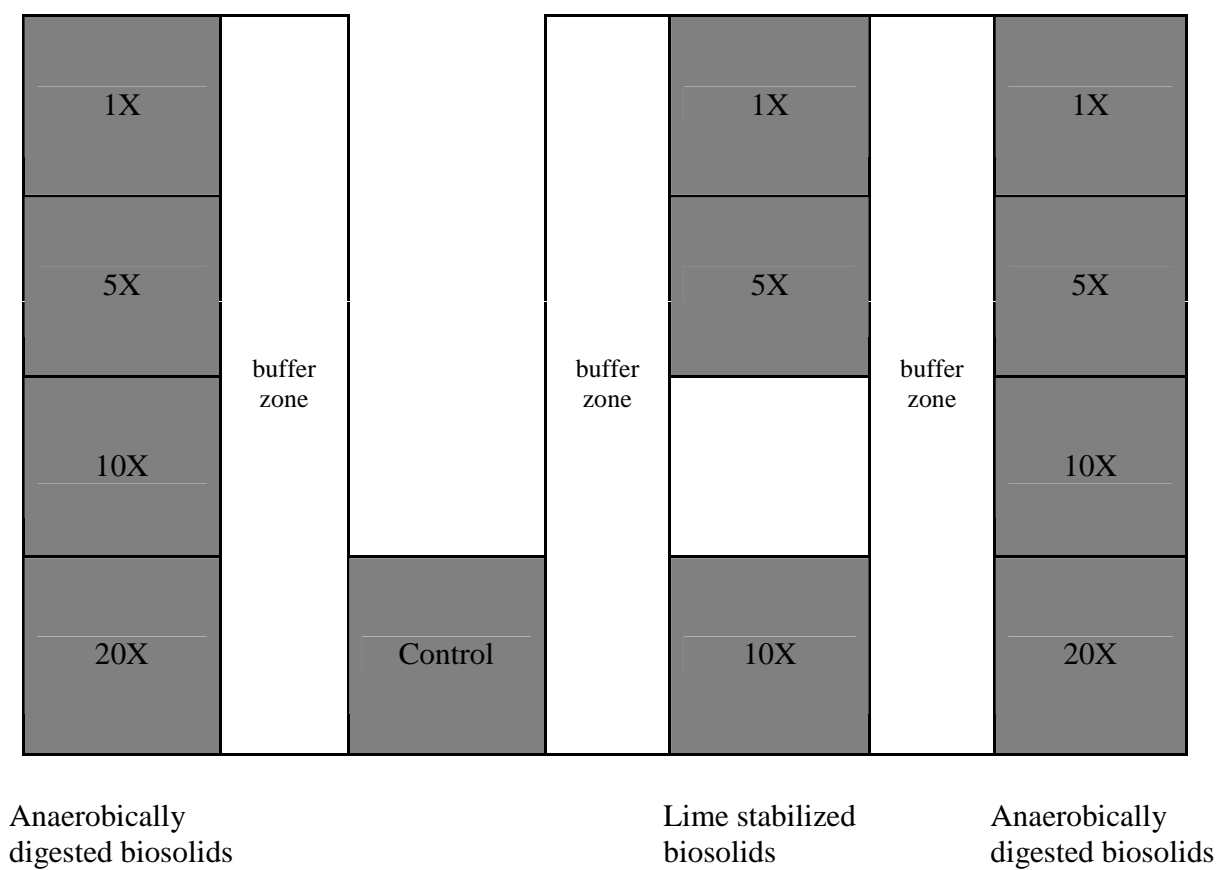


Figure 5. Layout of biosolids-amended test sites.

CHAPTER IV
NITROGEN IN BIOSOLIDS-AMENDED RANGELANDS

pH

High pH (7.7-8.6) was found in soil background at this study site (Table 3). Small discernable pH changes occurred at lime-stabilized biosolids-amended test sites in both years (Table 7). This is presumably due to the large doses of lime added during the biosolids processing. However, soil pH in aerobically digested and anaerobically digested biosolids-amended soils (Tables 8-9) remained unchanged following land application of biosolids. This was likely due to the buffering capacity of the soil. Refer to Appendix A for details about pH statistical analyses.

Table 7. Statistical analyses of pH in soil amended with lime-stabilized biosolids

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.3785	no	0.0077	no
	0.6	0.0328	higher	0.313	higher
	0.9	<0.0001	higher	0.7478	lower
	1.2	<0.0001	higher	0.8166	higher
	1.5	0.0964	no	0.8968	no
5X	0.2	1.0000	no	0.2005	no
	0.6	0.0326	higher	0.1782	lower
	0.9	0.387	no	0.0586	no
	1.2	0.7383	no	0.0567	no
	1.5	1.0000	no	0.0005	no
10X	0.2	0.9762	no	0.0015	no
	0.6	0.0916	no	0.1045	no
	0.9	0.0803	no	0.0327	no
	1.2	0.1463	no	0.0561	no
	1.5	0.0078	lower	0.0008	lower

Table 8. Statistical analyses of pH in soil amended with aerobically digested biosolids

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.6331	no	0.0038	lower
	0.6	0.0962	no	0.2443	no
	0.9	0.1658	no	0.4321	no
	1.2	0.2969	no	0.7748	no
	1.5	0.1944	no	0.6139	no
5X	0.2	0.6022	no	0.1872	no
	0.6	0.5201	no	0.0092	no
	0.9	0.1167	no	0.2128	no
	1.2	0.537	no	0.1801	no
	1.5	0.8396	no	0.0007	no
10X	0.2	0.644	no	0.0174	no
	0.6	0.4772	no	0.0246	no
	0.9	0.2183	no	0.0218	no
	1.2	0.7982	no	0.0234	no
	1.5	0.5772	no	0.0001	no
20X	0.2	0.3548	no	0.3148	no
	0.6	0.8642	no	0.6666	no
	0.9	0.3947	no	0.0738	no
	1.2	0.742	no	0.0698	no
	1.5	0.9474	no	0.0025	no

Electrical Conductivity (EC)

Electrical conductivity (EC), which measures salt content in soil, plays an important role in plant growth. At high EC values, it is difficult for plants to extract water from the soil to support their growth. Soil that had received lime-stabilized biosolids had unchanged EC in most cases (Table 10). However, at the biosolids application rate equal to the agronomic rate, EC in lime-stabilized biosolids-amended test site was lower than the control in both Year 1 and Year 2. At 5X and 10X the agronomic rate in year 2, EC was higher at 0.6-1.5 m depths. In aerobically digested biosolids-amended test sites, EC did not change in year 1 but changed slightly in Year 2 (Table 11). EC values at 0.9-1.5

m depths at the site receiving 1X application rate were lower than the control while it was higher at higher application rates (i.e., 5X, 10X, and 20X the agronomic rate) at soil depths ranging from 0.6 to 1.5 m. EC remained unchanged in both years in anaerobically digested biosolids-amended sites following biosolids application (Table 12). The lower EC values at the biosolids-amended test sites could be a result of soil heterogeneity and soil texture. Meanwhile, low precipitation could result in high EC values at the biosolids application sites since the salt content was not lost through leaching. Details of statistical analyses are found in Appendix B.

Table 9. Statistical analyses of pH in soil amended with anaerobically digested biosolids

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.6679	no	0.0154	no
	0.6	0.2717	no	0.0473	no
	0.9	0.1476	no	0.0317	no
	1.2	0.1968	no	0.04	no
	1.5	0.0865	no	0.0004	no
5X	0.2	0.454	no	0.0238	no
	0.6	0.6772	no	0.8767	no
	0.9	0.3021	no	0.1823	no
	1.2	0.5481	no	0.1376	no
	1.5	0.3035	no	0.0035	no
10X	0.2	0.3919	no	0.0865	no
	0.6	0.5946	no	0.1034	no
	0.9	0.4324	no	0.2186	no
	1.2	0.4707	no	0.1651	no
	1.5	0.922	no	0.0033	no
20X	0.2	0.9229	no	0.0094	no
	0.6	0.5591	no	0.17	no
	0.9	0.0853	no	0.2592	no
	1.2	0.1408	no	0.1431	no
	1.5	0.0051	higher	0.0293	lower

Table 10. Statistical analyses of EC in soil amended with lime-stabilized biosolids

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.009	lower	0.4395	no
	0.6	0.0434	lower	0.1123	no
	0.9	0.0136	lower	0.0093	lower
	1.2	0.004	lower	0.0251	lower
	1.5	0.0143	lower	0.0059	lower
5X	0.2	0.0782	no	0.3963	no
	0.6	0.818	no	0.0539	no
	0.9	0.9445	no	0.0927	no
	1.2	0.5937	no	0.0256	higher
	1.5	0.7606	no	0.0172	higher
10X	0.2	0.1589	no	0.0707	no
	0.6	0.9934	no	0.0468	higher
	0.9	0.59	no	0.0442	higher
	1.2	0.575	no	0.0698	no
	1.5	0.2135	no	0.1025	no

Nitrogen in Biosolids-amended Soil

The $\text{NH}_4\text{-N}$ soil concentrations in the control plot remained fairly constant with depths while NO_3 levels increased with depths. This could be explained by the soil heterogeneity and by the fact that data were not collected at the same subplots at each sampling time. It should be noted that the soil samples were collected in Year 2 following biosolids application. At the test site receiving lime-stabilized biosolids at 1X the agronomic rate, $\text{NH}_4\text{-N}$ levels were not statistically different from the control (Figure 6a and Table 13) and $\text{NO}_3\text{-N}$ level was statistically higher than the control at the depth of 1.5 m (Figure 7a and Table 14). This observation suggested that volatilization of ammonia at the soil surface might have been significant. The same pattern for $\text{NH}_4\text{-N}$ level was found at the 5X agronomic rate test site. Nitrification might have occurred up to the soil depth of 0.6 m as $\text{NO}_3\text{-N}$ levels were statistically higher than the control. Levels of $\text{NH}_4\text{-N}$ were

significantly lower than the control at 0.2-1.5 m depths at a loading rate equivalent to 10X the estimated agronomic rate. The low $\text{NH}_4\text{-N}$ at the soil surface (0.2 m) could be due to nitrification. The $\text{NO}_3\text{-N}$ levels at 0.9-1.5 m depths were not different from the control.

Ammonia volatilization at the soil surface likely occurred at the aerobically digested biosolids-amended test site at test plots receiving biosolids at 1X the estimated agronomic rate (Figure 6b and Table 13). Lower levels of $\text{NH}_4\text{-N}$ were found at 0.2 m as well as 0.9-1.5 m as compared with the control. Meanwhile, $\text{NO}_3\text{-N}$ accumulation only existed at 0.9-1.5 m depths (Figure 7b and Table 14), which indicates nitrification was occurring. Ammonia volatilization could have been significant on the plots receiving 5X the estimated agronomic rate when $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ accumulations were not present at the soil surface (0.2 m). The $\text{NH}_4\text{-N}$ levels were significantly lower than the control at 0.9 and 1.5 m depths. The $\text{NO}_3\text{-N}$ levels at 0.2-1.5 m depths were the same as the control. At 10X agronomic rate, $\text{NH}_4\text{-N}$ levels were found statistically lower than the control at up to 1.2 m of soil depth but levels of $\text{NO}_3\text{-N}$ exhibited a reversed pattern at up to 0.6 m of soil depth, which implied that nitrification could have occurred. Differences in $\text{NO}_3\text{-N}$ were not found at 0.9–1.5 m compared against the control. Levels of $\text{NH}_4\text{-N}$ at 0.2-1.5 m were not statistically different from the control while those of $\text{NO}_3\text{-N}$ were greater than the control at 20X agronomic rate. These observations suggested that nitrification took place at the site.

Statistical analyses indicated that nitrification could be dominant at the soil pths in most test sites except that $\text{NO}_3\text{-N}$ accumulation was also found at 0.6-1.2 m depths at 5X agronomic rate. $\text{NH}_4\text{-N}$ concentrations at 1X agronomic rate could not be presented due

to data incomplete analysis. Again, nitrification probably occurred due to favorably aerobic conditions at the soil surface (i.e. well-drained soil surface (0.2 m) as level of $\text{NH}_4\text{-N}$ was not statistically different from the control in anaerobically digested biosolids-amended test site at 5X agronomic rate (Figure 6c and Table 13). The finding was consistent with $\text{NO}_3\text{-N}$ accumulation present at the soil surface at this biosolids-amended site (Figure 7c and Table 14). $\text{NO}_3\text{-N}$ did not accumulate at lower soil decondition). Statistical reports are presented in Appendices C and D.

Table 11. Statistical analyses of EC in soil amended with aerobically digested biosolids

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.2219	no	0.4319	no
	0.6	0.6499	no	0.0834	no
	0.9	0.2655	no	0.0301	lower
	1.2	0.3547	no	0.0211	lower
	1.5	0.3213	no	0.0287	lower
5X	0.2	0.0584	no	0.3827	no
	0.6	0.0604	no	0.0033	higher
	0.9	0.9798	no	0.0314	higher
	1.2	0.2495	no	0.1066	no
	1.5	0.367	no	0.4737	no
10X	0.2	0.5488	no	0.1057	no
	0.6	0.3701	no	0.0648	no
	0.9	0.8368	no	0.0063	higher
	1.2	0.5742	no	0.0008	higher
	1.5	0.5756	no	0.0094	higher
20X	0.2	0.1434	no	0.1823	no
	0.6	0.6884	no	0.1536	no
	0.9	0.6989	no	0.0301	higher
	1.2	0.9777	no	0.0074	higher
	1.5	0.6627	no	0.0676	no

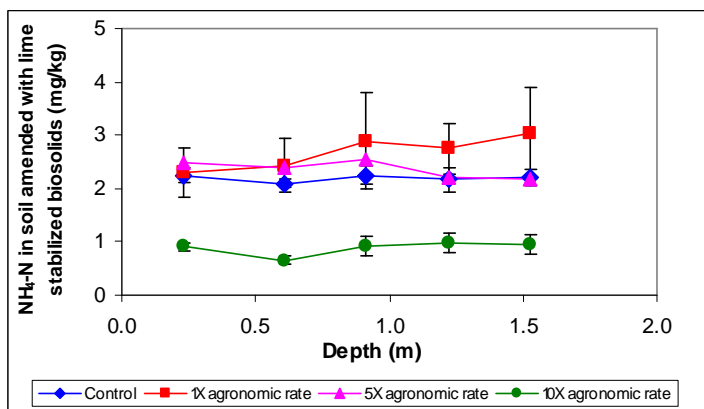
Table 12. Statistical analyses of EC in soil amended with anaerobically digested biosolids

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.8425	no	0.054	no
	0.6	0.0116	lower	0.1695	no
	0.9	0.2015	no	0.0349	no
	1.2	0.8563	no	0.0238	no
	1.5	0.3403	no	0.0072	no
5X	0.2	0.5884	no	0.2163	no
	0.6	0.1791	no	0.7543	no
	0.9	0.1172	no	0.5677	no
	1.2	0.7198	no	0.0964	no
	1.5	0.6188	no	0.249	no
10X	0.2	0.956	no	0.0934	no
	0.6	0.6069	no	0.2193	no
	0.9	0.3802	no	0.8731	no
	1.2	0.8756	no	0.7848	no
	1.5	0.7146	no	0.5024	no
20X	0.2	0.8248	no	0.9164	no
	0.6	0.1434	no	0.8328	no
	0.9	0.3384	no	0.6097	no
	1.2	0.6849	no	0.6647	no
	1.5	0.5244	no	0.7395	lower

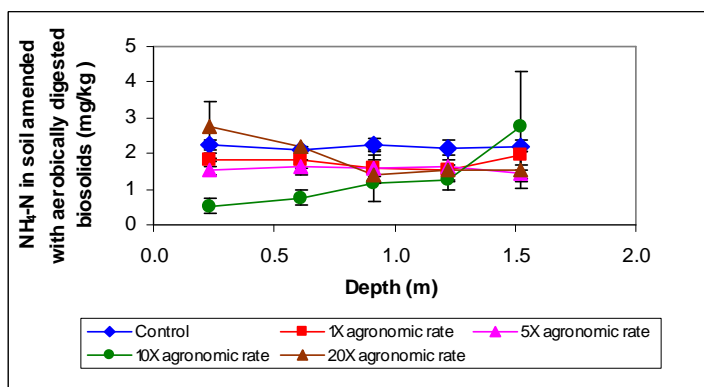
Nitrogen Mass Balance

The nitrogen balance was calculated assuming that the N concentration at a depth of 0.2 m reflected an average N concentration throughout the 0.3 m soil depth. The mass balance was then conducted over a control volume equal to the first 0.3 m of soil. In addition to a constant soil nitrogen concentration, the N mass balance also assumed that the soil bulk density throughout the 0.3 m of soil depth remained constant.

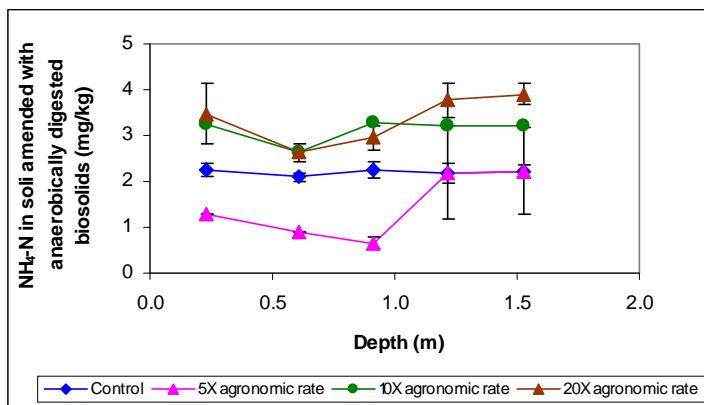
In Tables 15-17, the difference between the amount of N applied (kg/ha) and the measured uptake of N by vegetation (kg/ha) is called the nitrogen residual. N plant uptake was calculated by multiplication of N concentration in plant tissue (mg/kg) and



(a)

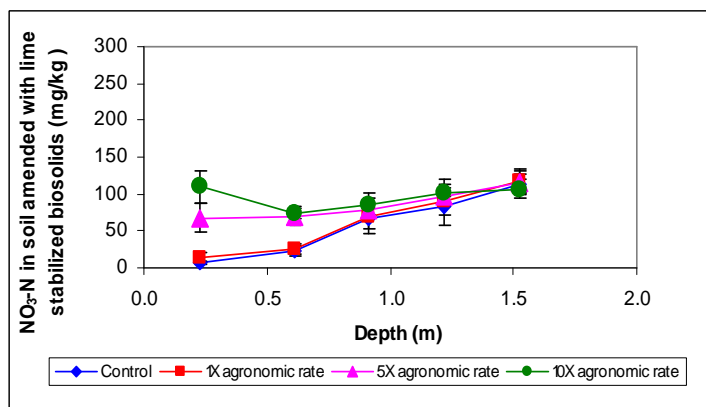


(b)

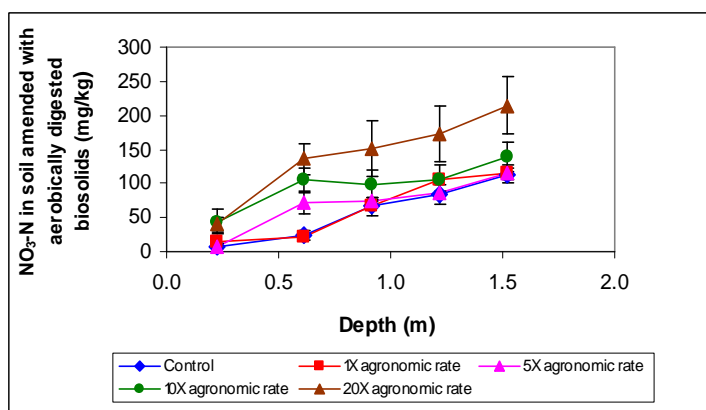


(c)

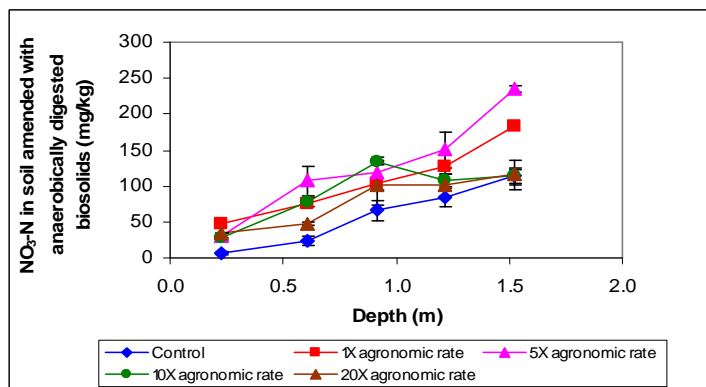
Figure 6. Ammonium ($\text{NH}_4\text{-N}$) in soil amended with (a) lime-stabilized biosolids, (b) aerobically digested biosolids, and (c) anaerobically digested biosolids. The error bars represent the standard errors based on variation in six subplots. The $\text{NH}_4\text{-N}$ data at the 1X agronomic rate were missing for anaerobically digested biosolids-amended soil.



(a)



(b)



(c)

Figure 7. Nitrate ($\text{NO}_3\text{-N}$) in soil amended with (a) lime-stabilized biosolids, (b) aerobically digested biosolids, and (c) anaerobically digested biosolids. The error bars represent the standard errors based on variation in six subplots.

Table 13. Statistical analyses of NH₄-N in biosolids application sites

Biosolids	Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
Lime-stabilized	1X	0.2	0.8976	no
		0.6	0.6555	no
		0.9	0.4078	no
		1.2	0.9313	no
		1.5	0.9524	no
	5X	0.2	0.4552	no
		0.6	0.6117	no
		0.9	0.2674	no
		1.2	0.2765	no
		1.5	0.2064	no
	10X	0.2	<0.0001	lower
		0.6	0.0097	lower
		0.9	0.0196	lower
		1.2	0.0002	lower
		1.5	0.0017	lower
Aerobically digested	1X	0.2	0.0011	lower
		0.6	0.0528	no
		0.9	0.0325	lower
		1.2	0.0145	lower
		1.5	0.0049	lower
	5X	0.2	0.0006	lower
		0.6	0.5133	no
		0.9	0.0342	lower
		1.2	0.051	no
		1.5	0.0028	lower
	10X	0.2	<0.0001	lower
		0.6	0.042	lower
		0.9	0.0088	lower
		1.2	0.0318	lower
		1.5	0.4462	no
	20X	0.2	0.0731	no
		0.6	0.0684	no
		0.9	0.079	no
		1.2	0.0537	no
		1.5	0.4747	no
Anaerobically digested	1X	0.2	NA*	NA*
		0.6	NA*	NA*
		0.9	0.1121	no
		1.2	<0.0001	lower
		1.5	0.0023	lower

*The original data were missing.

Table 13. Continued

Biosolids	Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
Anaerobically digested	5X	0.2	0.0734	no
		0.6	0.002	lower
		0.9	<0.0001	lower
		1.2	0.9648	no
		1.5	0.9822	no
	10X	0.2	0.0031	higher
		0.6	0.083	no
		0.9	<0.0001	higher
		1.2	0.1412	no
		1.5	0.0011	higher
	20X	0.2	0.0123	higher
		0.6	0.0155	higher
		0.9	0.0023	higher
		1.2	0.0029	higher
		1.5	<0.0001	higher

Table 14. Statistical analyses of NO₃-N in biosolids application sites

Biosolids	Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
Lime-stabilized	1X	0.2	0.2266	no
		0.6	0.2461	no
		0.9	0.1231	no
		1.2	0.0592	no
		1.5	0.0255	higher
	5X	0.2	0.0006	higher
		0.6	0.0028	higher
		0.9	0.5368	no
		1.2	0.5831	no
		1.5	0.8991	no
	10X	0.2	<0.0001	higher
		0.6	0.0036	higher
		0.9	0.3832	no
		1.2	0.4361	no
		1.5	0.483	no
Aerobically digested	1X	0.2	0.8599	no
		0.6	0.1785	no
		0.9	0.04	higher
		1.2	0.0205	higher
		1.5	0.0023	higher

Table 14. Continued

Biosolids	Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
Aerobically digested	5X	0.2	0.7392	no
		0.6	0.2658	no
		0.9	0.3161	no
		1.2	0.2082	no
		1.5	0.0998	no
	10X	0.2	0.0118	higher
		0.6	<0.0001	higher
		0.9	0.2004	no
		1.2	0.4143	no
		1.5	0.3089	no
	20X	0.2	0.001	higher
		0.6	<0.0001	higher
		0.9	0.0261	higher
		1.2	0.0201	higher
		1.5	0.0092	higher
Anaerobically digested	1X	0.2	<0.0001	no
		0.6	0.004	no
		0.9	0.0403	no
		1.2	0.023	no
		1.5	0.0032	no
	5X	0.2	0.0127	higher
		0.6	0.0217	higher
		0.9	0.9833	no
		1.2	0.7275	higher
		1.5	0.0713	no
	10X	0.2	0.0363	higher
		0.6	0.0336	no
		0.9	0.5208	no
		1.2	0.6387	no
		1.5	0.1502	no
	20X	0.2	0.0653	higher
		0.6	0.7046	no
		0.9	0.9942	no
		1.2	0.1005	no
		1.5	0.0275	higher

biomass yield (kg/ha) The nitrogen residual is compared to the nitrogen accumulation, which is simply the measured N concentration (at the 0.2 m depth) minus the N concentration in the control multiplied by the volume of soil in the first 0.3-m depth.

In all cases, the difference between the nitrogen residual measurement and the nitrogen accumulation was significant. The large differences may be attributed to the following factors: nitrate movement to soil surface due to higher evapotranspiration at the study site, nitrogen volatilization as NH_4 due to wild fire, heterogeneity of the soil (i.e., use of constant N and bulk density value throughout the soil profile is inappropriate), greater ammonia volatilization than predicted, potential deposition from atmospheric sources, removal of nitrogen through denitrification, loss of nitrogen through wind erosion, and transport of nitrogen to depths below soil surface (0.2 m).

Table 15. N mass balance in lime-stabilized biosolids-amended soil

Lime stabilized biosolids				
Multiple of agronomic rate	N applied (kg/ha)	Plant uptake (kg/ha)	N Residual (kg/ha)	N accumulation (kg/ha)
1X	175.73	10.13	165.60	450.57
5X	878.67	5.46	873.21	525.22
10X	1757.35	4.42	1752.93	197.23
20X	NA*	NA*	NA*	NA*

*Lime stabilized biosolids were not applied at 20X estimated agronomic rate due to their low nitrogen concentration.

Table 16. N mass balance in aerobically digested biosolids-amended soil

Aerobically digested biosolids				
Multiple of agronomic rate	N applied (kg/ha)	Plant uptake (kg/ha)	N Residual (kg/ha)	N accumulation (kg/ha)
1X	186.10	7.01	14.71	-543.20
5X	931.60	6.04	12.48	-396.64
10X	1863.20	5.00	1858.20	-426.60
20X	3726.41	2.60	3723.81	489.80

Table 17. N mass balance in anaerobically digested biosolids-amended soil

Anaerobically digested biosolids				
Multiple of agronomic rate	N applied (kg/ha)	Plant uptake (kg/ha)	N Residual (kg/ha)	N accumulation (kg/ha)
1X	167.24	5.60	161.64	480.54
5X	836.18	3.48	832.7	239.73
10X	1672.37	2.81	1669.56	403.17
20X	3344.74	1.83	3342.91	737.70

The Root Zone Water Quality Model (RZWQM) Simulation

The storage of ammonium (NH₄) and nitrate (NO₃) in biosolids-amended test sites was simulated by the RZWQM model for a 1-year period. In this simulation, total accumulation of NH₄ and NO₃ was predicted to a depth of up to 1.2 m below the ground surface (i.e. the maximum soil depth at which the RZWQM model was designed for simulation). Based on model default choices, winter wheat crop was chosen as the simulated crop instead of cheatgrass, which is the dominant species on the rangeland test sites. This decision was made because the RZWQM model was originally parameterized for corn, soybean, and winter wheat crops, and winter wheat and cheatgrass have similar growth patterns (Ransom, 2007).

The NH₄ and NO₃ storage from the field data were totaled from the storage of NH₄ at five soil depths (i.e. 0.2-, 0.6-, 0.9-, 1.2-, and 1.5-m depths) at which the soil samples were collected and analyzed for NH₄ and NO₃ concentration. At each single soil depth, accumulation of NH₄ or NO₃ (kg/ha) was calculated based on its mass concentration (mg/kg) and soil bulk density (1.43 g/cm³). The total NH₄ or NO₃ storage was the sum of NH₄ or NO₃ storage at each soil depth.

$$\text{NH}_4 \text{ accumulation (kg/ha)} = (\text{NH}_4 \text{ in biosolids} - \text{NH}_4 \text{ in control}) \frac{\text{mg NH}_4}{\text{kg soil}} \times \text{depth (ft)} \times \frac{12 \text{ in}}{1 \text{ ft}} \times \frac{2.54 \text{ cm}}{1 \text{ in}} \\ \times 1.43 \frac{\text{g}}{\text{cm}^3} \times \frac{1 \text{ kg soil}}{1000 \text{ g soil}} \times \frac{1 \text{ kg NH}_4}{10^6 \text{ mg NH}_4} \times \frac{1 \text{ cm}^2}{10^{-8} \text{ ha}}$$

$$\text{NO}_3 \text{ accumulation (kg/ha)} = (\text{NO}_3 \text{ in biosolids} - \text{NO}_3 \text{ in control}) \frac{\text{mg NO}_3}{\text{kg soil}} \times \text{depth (ft)} \times \frac{12 \text{ in}}{1 \text{ ft}} \times \frac{2.54 \text{ cm}}{1 \text{ in}} \\ \times 1.43 \frac{\text{g}}{\text{cm}^3} \times \frac{1 \text{ kg soil}}{1000 \text{ g soil}} \times \frac{1 \text{ kg NO}_3}{10^6 \text{ mg NO}_3} \times \frac{1 \text{ cm}^2}{10^{-8} \text{ ha}}$$

The simulated storage of NH₄ and NO₃ at the treatment sites that had received lime-stabilized biosolids are shown in Table 18 along with the results obtained from the

field data. Significant differences between the simulated and field data were found in both NH_4 and NO_3 storage.

The field NH_4 and NO_3 storage values were lower than the predicted values except that the field NH_4 was higher than the predicted value at 1X agronomic rate. The negative values of the field NH_4 storage in some cases (Tables 18-20) were due to the lower concentrations of NH_4 at the biosolids-amended test sites than the control plot.

The simulated NO_3 storage in the test treatments amended with aerobically digested biosolids was higher than the recorded field values (Table 19). The same pattern was found for simulated NH_4 results as they were higher than the field data at all biosolids application rates. Showing the same trend with the test sites receiving aerobically digested biosolids, the simulated NH_4 and NO_3 storage in the test treatments amended with anaerobically digested biosolids (Table 20) was higher than the field values at all biosolids application rates .

The differences between the simulation results from the RZWQM model and the field data could be due to a number of reasons. First, the NH_4 and NO_3 storage from the field data were only based on NH_4 and NO_3 one-time mass concentrations, which were analyzed from 2006 field samples, whereas the simulated NH_4 and NO_3 storages were executed over a 1-year period (i.e. from the beginning of 2006 until the end of 2006). Secondly, as shown in Chapter IV, the concentrations of NH_4 and NO_3 from the field data did not exhibit a consistent trend at various soil depths and biosolids application rates. The assumption of constant soil bulk density at different soil depths for NH_4 and NO_3 storage calculation in biosolids-amended treatment sites could explain, at least in part, the differences found between the field results and simulated results. Lastly, the RZWQM

program might have overstated rates of microbial processes needed for nitrification and denitrification. Limited moist was present at the study site as well as high evapotranspiration, which did not favor microbial activities for nitrogen mineralization.

Given the lack of field validated input parameters available for the RZWQM simulation, default values were used. Use of default values could explain the poor correlation between the model simulation and the field data. As shown in Table 21, the RZWQM requires an extensive level of detailed parameter for adequate simulation. Some parameters (e.g. organic matter/N cycling) need to be calibrated for accurate simulations, which is impossible in practical conditions (Malone et al., 2000). In addition, the various moisture transport processes (e.g., runoff, percolation, etc.) simulated in the RZWQM are interrelated meaning that a poor estimate in parameter value for one process could negatively impact the accuracy of another process. Other researchers have found similar results to the ones reported in this study. For example, if a layer of low permeability is encountered, the model has been found to have difficulty in simulating the soil NO₃ profile (Ma et al., 1998a, 1998b; Nokers, Landa, and Hanson, 1996; Jaynes and Miller, 1999).

In order to simulate NO₃ storage, the source code of the RZWQM must be modified to address a biosolids-amended rangeland system. For example, cropping system and plant growth should be parameterized according to cheatgrass or other appropriate vegetation. To date, all available models are solely for nutrient simulation in typical agricultural cropping systems. Therefore, a unique model for biosolids-amended rangeland system needs to be developed. To conduct future simulations focused on biosolids application to disturbed rangelands, the following performance objectives

should be addressed: a) loading rate of biosolids application that does not pose a risk NO_3 contamination of ground water, b) change of NO_3 levels at various soil depths, c) NO_3 in runoff flow and d) best timing and method application of biosolids.

Table 18. Nitrogen profile obtained from field data and the RZWQM model for soil amended with lime-stabilized biosolids

Biosolids application rate (Multiple of agronomic rate)	NH ₄ storage		NO ₃ storage	
	(kg NH ₄ or NO ₃ /ha)			
	Field sampling	Simulation	Field sampling	Simulation
1X	7.38	0.55	72.03	363.34
5X	3.88	36.36	559.92	910.54
10X	-23.16	125.57	772.05	1638.10
20X	NA	NA	NA	NA

Table 19. Nitrogen profile obtained from field data and the RZWQM model for soil amended with aerobically digested biosolids

Biosolids application rate (Multiple of agronomic rate)	NH ₄ storage		NO ₃ storage	
	(kg/ha)			
	Field sampling	Simulation	Field sampling	Simulation
1X	-8.66	0.43	115.23	363.30
5X	-10.21	9.46	314.85	706.81
10X	-21.57	125.21	804.46	1635.39
20X	-4.42	1134.8	1473.80	4436.26

Table 20. Nitrogen profile obtained from field data and the RZWQM model for soil amended with anaerobically digested biosolids

Biosolids application rate (Multiple of agronomic rate)	NH ₄ storage		NO ₃ storage	
	(kg/ha)			
	Field sampling	Simulation	Field sampling	Simulation
1X	-27.86	0.59	761.57	363.37
5X	-16.54	9.77	1047.91	706.22
10X	15.24	125.87	765.36	1635.21
20X	17.03	1142.61	453.66	4395.47

Table 21. Summary of RZWQM parameters needed

Parameters	Default value	Measured value
daily meteorology file		from CLIGEN90 weather generator
breakpoint rainfall file		from CLIGEN90 weather generator
snowpack dynamics file		From CLIGEN90 weather generator
soil type		x

Table 21. Continued

Parameters	Default value	Measured value
particle density	x	
bulk density	x	
porosity	x	
sand/silt/clay fraction	x	
saturated hydraulic conductivity		x
field capacity water content	x	
total macroporosity	x	
fraction dead-end macropores	x	
average radius of cylindrical pore	x	
width of cracks	x	
length of cracks	x	
depth of cracks	x	
hydraulics control	x	
irrigation water chemistry	NA	NA
rain water chemistry	x	
albedo of dry soil	x	
albedo of wet soil	x	
albedo of crop at maturity	x	
albedo of fresh residue	x	
average daily sunshine fraction	x	
wind measurement height	x	
C:N ratio in slow residue pool	x	
C:N ratio in fast residue pool	x	
C:N ratio in fast soil humus pool	x	
C:N ratio in transition soil humus pool	x	
C:N ratio aerobic heterotrophs pool	x	
C:N ratio in autotrophs pool	x	
C:N ratio anaerobic heterotrophs pool	x	
anhydrous NH ₃ applied	NA	NA
volumetric water content		x
soil pH		x
soil CEC	x	
fraction exchangeable ions (Ca, Na, Mg...)	x	
partial pressure CO ₂ gas	x	
pesticide state	NA	NA
initial residue profile	x	
surface residue properties	x	
crop selection	x	
crop planting	NA	NA
plant growth	x	
manure inputs		substituted by biosolids inputs

Table 21. Continued

Parameters	Default value	Measured value
irrigation	NA	NA
fertilization	NA	NA
pesticides	NA	NA
tillage	NA	NA

Biomass Yield

Biomass yield in biosolids-amended test sites was significantly affected by biosolids land application as shown in Table 22. Biomass production in the test plots that had received lime-stabilized, aerobically digested and anaerobically digested biosolids at different loading rates was significantly higher as compared against the biomass production in the control (132.7 ± 94.1 kg/ha). The test plot that had received anaerobically digested biosolids at the agronomic rate (i.e., 1X) was exceptional as its biomass production was not statistically different from the control. Standard errors from six subplots were represented after “ \pm ” in each data point. Biomass production did not show any consistent trend with increasing biosolids application rates, which may be attributed to the high variability in biomass levels. Despite the variable trend in biomass production, biosolids applications resulted in enhanced biomass yield as compared against the control.

Table 22. Biomass yields (kg/ha)* in biosolids-amended test plots

Biosolids type	Biosolids application rate (Multiple of agronomic rate)			
	1X	5X	10X	20X
Lime stabilized biosolids	1169.1 \pm 224.7	633.0 \pm 187.4	602.7 \pm 61.1	NA
Aerobically digested biosolids	697.4 \pm 170.0	778.3 \pm 159.5	772.3 \pm 103.1	1182.5 \pm 341.0
Anaerobically digested biosolids	251.9 \pm 79.9	495.6 \pm 100.1	462.4 \pm 100.1	728.6 \pm 200.8

*Based on dry weight

Plant Speciation

Nine plant types were identified at this study site including cheatgrass, mouse barley, hornseed buttercup, fireweed, herb Sophia, bulbous bluegrass, clasping peppergrass, tall tumbled mustard, and sticky purple geranium. The dominant species in the control were found to be cheatgrass (45.3%) and hornseed buttercup (45.3%). Mouse barley was also present with a small percentage (6.9%). The other plant types appeared to be negligible with their percentage ranging from 0 to 1.4% (Tables 23-25).

Lime-stabilized biosolids supported the growth of mouse barley which was illustrated by the increasing percentage of mouse barley as increasing biosolids loading rate (Table 23). In contrast, the hornseed buttercup was dominant in the control but its growth apparently declined significantly in sites that received lime stabilized biosolids. Cheatgrass growth was highest in site that received lime-stabilized biosolids at the biosolids application rate equal to the agronomic rate. However, as the biosolids application rate increased, the percentage of cheatgrass declined to the level found in the control plot. Fireweed had a greater population in biosolids-amended sites.

In sites that received aerobically digested biosolids, the dominant growth was represented by mouse barley. Its percentage in biosolids-amended sites increases with increasing biosolids application rates (Table 24). There was an exception at the 20X agronomic rate when the percentage of mouse barley decreased. Cheatgrass showed constant growth except at the sites that receive a biosolids loading rate equivalent to twenty times the agronomic rate. The hornseed buttercup percentage also declined in biosolids-amended sites as compared with the control.

Cheatgrass growth in sites that received anaerobically digested biosolids at biosolids loading rates of 1X and 5X agronomic rate was lower than that found in the control (Table 25). However, cheatgrass population appeared to be denser at higher biosolids loading rates (i.e., 10X and 20X estimated agronomic rate). The growth of mouse barley and hornseed buttercup exhibited the same trend with those in sites that received lime-stabilized and aerobically digested biosolids. The percentage of herb *Sophia* was higher in sites that received biosolids at 1X, 5X, and 10X agronomic rate.

There was apparently a nutrient competition among the plant types in biosolids-amended test sites. This was illustrated by the dominant population of mouse barley in sites that received lime-stabilized, aerobically digested, and anaerobically digested biosolids. As mentioned previously, $\text{NH}_4\text{-N}$ concentrations in biosolids-amended sites in this study were low even at high biosolids loading rates due to high ammonia volatilization (Figure 6). Therefore, soil nitrogen (i.e., $\text{NH}_4\text{-N}$) pool was low, which resulted in a competition among plants in order to survive. Nevertheless, nitrate ($\text{NO}_3\text{-N}$) concentrations in biosolids-amended sites (Figures 7a-c) were higher than the control at 0.2-0.6m depths, which could make up the deficiency of available $\text{NH}_4\text{-N}$ for plant uptake within the root zone. Generally, the root zone starts at 0.2-m and ends at 1.2-m soil depths, which varies among different plant types.

Cheatgrass and hornseed buttercup were found to be dominant species (45.3% for each) while mouse barley contributed a small percentage (6.9%) in the control site. As various types of biosolids were applied to soil at different application rates, the population of each plant type appeared to reverse. For example, mouse barley population

increased significantly as compared with that of the control. The hornseed population appeared to decline in biosolids-amended test sites. The cheatgrass population exhibited a more complex change in which it increased in sites with lime-stabilized and anaerobically digested biosolids application while it decreased in sites with aerobically digested biosolids application. This change of plant population in biosolids-amended sites could be attributed to nutrient competition.

Table 23. Plant types (%) in soil amended with lime-stabilized biosolids

			Biosolids application rate (multiple of agronomic rate)		
Plant type (%)	Common name	Control	1X	5X	10X
<i>Bromus tectorum</i>	cheatgrass	45.3	72.5	51.5	46.5
<i>Hordeum murinum</i>	mouse barley	6.9	18.4	35.2	32.0
<i>Ranunculus testiculatus</i>	hornseed buttercup	45.3	4.2	10.6	12.9
<i>Kochia scoparia</i>	fireweed	1.1	3.6	0.0	7.9
<i>Descurainia sophia</i>	herb sophia	0.0	0.0	1.1	0.4
<i>Poa bulbosa</i>	bulbous bluegrass	0.0	0.0	1.1	0.0
<i>Lepidium perfoliatum</i>	clasping peppergrass	1.4	0.0	0.4	0.0
<i>Sisymbrium altissimum</i>	tall tumbled mustard	0.0	0.0	0.0	0.4
<i>Geranium viscosissimum</i>	sticky purple geranium	0.0	1.2	0.0	0.0
Total		100	100	100	100

Table 24. Plant types (%) in soil amended with aerobically digested biosolids

			Biosolids application rate (multiple of agronomic rate)			
Plant type (%)	Common name	Control	1X	5X	10X	20X
<i>Bromus tectorum</i>	cheatgrass	45.3	45.3	41.7	26.7	41.6
<i>Hordeum murinum</i>	mouse barley	6.9	22.8	31.8	38.7	25.7
<i>Ranunculus testiculatus</i>	hornseed buttercup	45.3	30.9	24.4	31.4	24.3
<i>Kochia scoparia</i>	fireweed	1.1	0.0	1.8	2.6	6.5
<i>Descurainia sophia</i>	herb sophia	0.0	0.0	0.0	0.5	1.9
<i>Poa bulbosa</i>	bulbous bluegrass	0.0	0.9	0.0	0.0	0.0
<i>Lepidium perfoliatum</i>	clasping peppergrass	1.4	0.0	0.4	0.0	0.0
<i>Sisymbrium altissimum</i>	tall tumbled mustard	0.0	0.0	0.0	0.0	0.0
<i>Geranium viscosissimum</i>	sticky purple geranium	0.0	0.0	0.0	0.0	0.0
Total		100	100	100	100	100

Table 25. Plant types (%) in soil amended with anaerobically digested biosolids

			Biosolids application rate (multiple of agronomic rate)			
Plant type (%)	Common name	Control	1X	5X	10X	20X
<i>Bromus tectorum</i>	cheatgrass	45.3	21.3	35.5	52.2	55.3
<i>Hordeum murinum</i>	mouse barley	6.9	58.6	37.6	25.8	35.1
<i>Ranunculus testiculatus</i>	hornseed buttercup	45.3	16.7	24.1	17.4	9.3
<i>Kochia scoparia</i>	fireweed	1.1	0.0	0.4	0.0	0.0
<i>Descurainia sophia</i>	herb sophia	0.0	0.4	1.2	2.5	0.0
<i>Poa bulbosa</i>	bulbous bluegrass	0.0	2.9	0.8	0.6	0.3
<i>Lepidium perfoliatum</i>	clasping peppergrass	1.4	0.0	0.0	0.0	0.0
<i>Sisymbrium altissimum</i>	tall tumbled mustard	0.0	0.0	0.4	0.0	0.0
<i>Geranium viscosissimum</i>	sticky purple geranium	0.0	0.0	0.0	1.6	0.0
Total		100	100	100	100	100

CHAPTER V
PHOSPHORUS MOBILITY ON BIOSOLIDS-AMENDED RANGELANDS

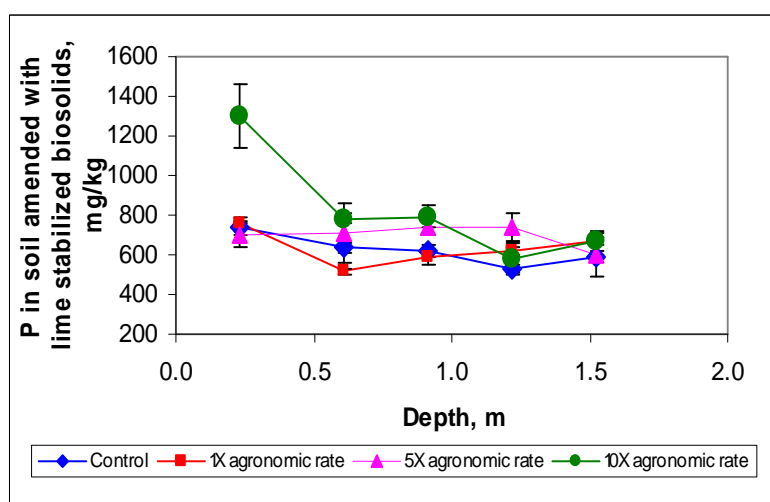
Total P

Levels of total P in lime-stabilized biosolids-amended soil as a function of depth are shown in Figure 8. In both Year 1 and 2, total P concentrations at the 10X agronomic rate were statistically higher at the soil surface (0.2 m) than the control (Table 26). This could be explained by the fact that P forms precipitates with soil metal species such as aluminum (Al), calcium (Ca), and iron (Fe). In some cases, total P levels were different from the control at depths ranging from 0.6 to 1.2 m (Table 26), which is attributable to soil variability.

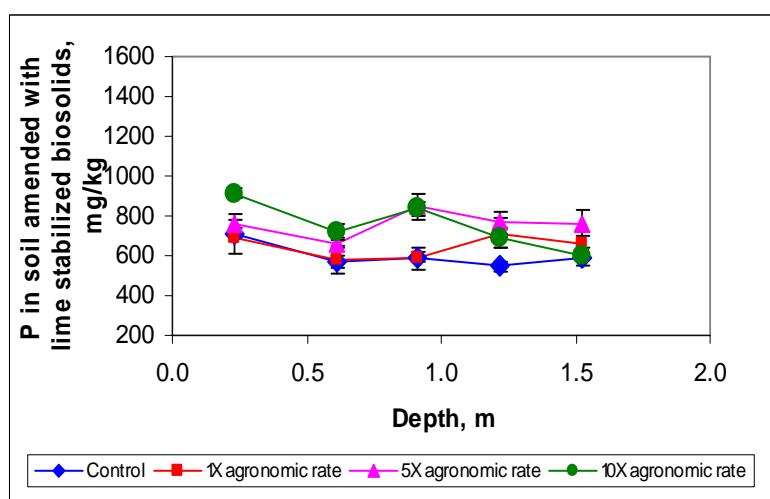
Figure 9 depicts the total P profiles from Year 1 and Year 2 after aerobically digested biosolids application. Total P in Year 2 tended to accumulate at the soil surface (0.2 m) in test sites receiving biosolids at rates equivalent to 10X and 20X the estimated agronomic rate (Table 27). In some cases, total P concentrations in both years were found to be significantly higher than the control at soil depths ranging from 0.6-1.2 m. However, levels of total P remained unchanged between Year 1 and Year 2 (Figure 9), which suggested that P was not lost through leaching below the root zone.

Accumulation of total P at the soil surface (0.2 m) in anaerobically digested biosolids-amended sites was present in Year 2 at the application rates of 5X to 20X agronomic rate (Figure 10 and Table 28). Levels of total P in Year 1 were not statistically different from the control in most cases. These P levels were also slightly lower than those in Year 2. These findings suggested that some organic P in soil amended with

anaerobically digested biosolids continued to be mineralized in Year 2. The trend of total P among test plots that had received three different types of biosolids could have been affected by biological and chemical activity including organic P mineralization. Refer to Appendix E for details about phosphorus statistical analyses.



(a)

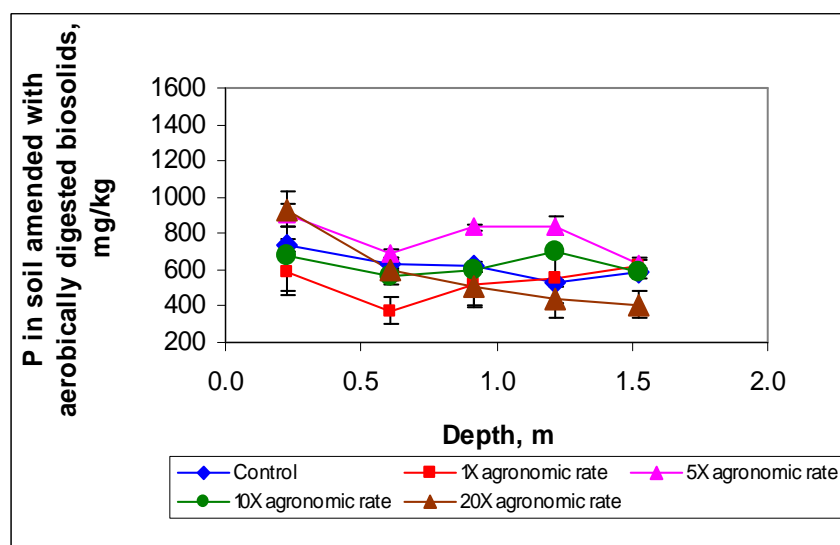


(b)

Figure 8. Total P from soil amended with lime-stabilized biosolids as (a) at the end of Year 1 and (b) at the end of Year 2. The error bars represent the standard errors.

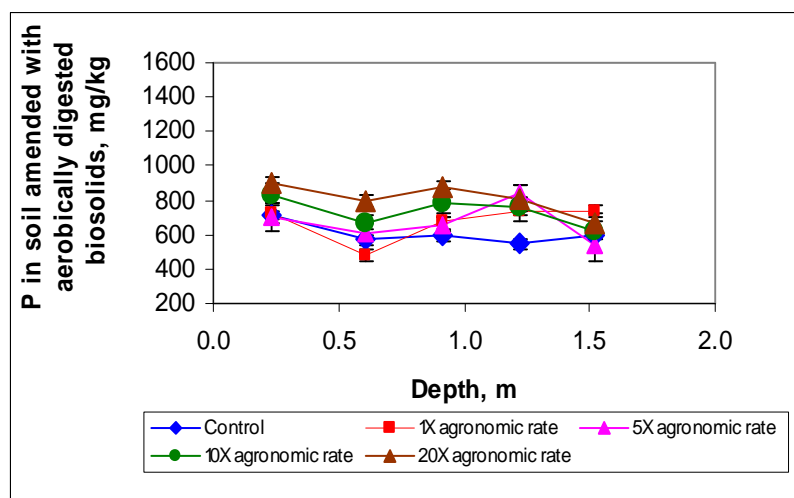
Table 26. Statistical analyses of total P in soil amended with lime-stabilized biosolids

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.7323	no	0.7949	no
	0.6	0.029	lower	0.9051	no
	0.9	0.6323	no	0.9375	no
	1.2	0.0434	higher	0.0187	higher
	1.5	0.0018	higher	0.2267	no
5X	0.2	0.6761	no	0.366	no
	0.6	0.4354	no	0.0658	no
	0.9	0.0578	no	0.0003	higher
	1.2	0.0018	higher	0.0006	higher
	1.5	0.8797	no	0.0031	higher
10X	0.2	0.0003	higher	0.0003	higher
	0.6	0.0119	higher	0.0118	higher
	0.9	0.0154	higher	< 0.0001	higher
	1.2	0.3187	no	0.0134	higher
	1.5	0.0313	higher	0.9308	no



(a)

Figure 9. Total P from soil amended with aerobically digested biosolids as (a) at the end of Year 1 and (b) at the end of Year 2. The error bars represent the standard errors.



(b)

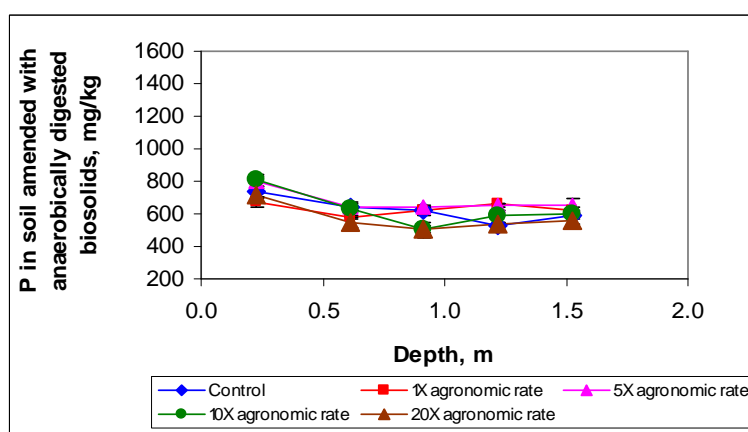
Figure 9. Continued.

Table 27. Statistical analyses of total P in soil amended with aerobically digested biosolids

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.1628	no	0.8584	no
	0.6	0.0013	lower	0.0735	no
	0.9	0.2221	no	0.0863	no
	1.2	0.7304	no	0.0032	higher
	1.5	0.2329	no	0.0007	higher
5X	0.2	0.0483	higher	0.8953	no
	0.6	0.3269	no	0.479	no
	0.9	0.0024	higher	0.1538	no
	1.2	<0.0001	higher	<0.0001	higher
	1.5	0.0779	no	0.3872	no
10X	0.2	0.6250	no	0.0499	higher
	0.6	0.1750	no	0.0604	no
	0.9	0.7297	no	0.0098	higher
	1.2	0.0009	higher	0.0011	higher
	1.5	0.7393	no	0.4712	no
20X	0.2	0.0416	higher	0.0006	higher
	0.6	0.4889	no	0.1017	no
	0.9	0.1529	no	<0.0001	higher
	1.2	0.2089	no	0.0009	higher
	1.5	0.0020	lower	0.0875	no

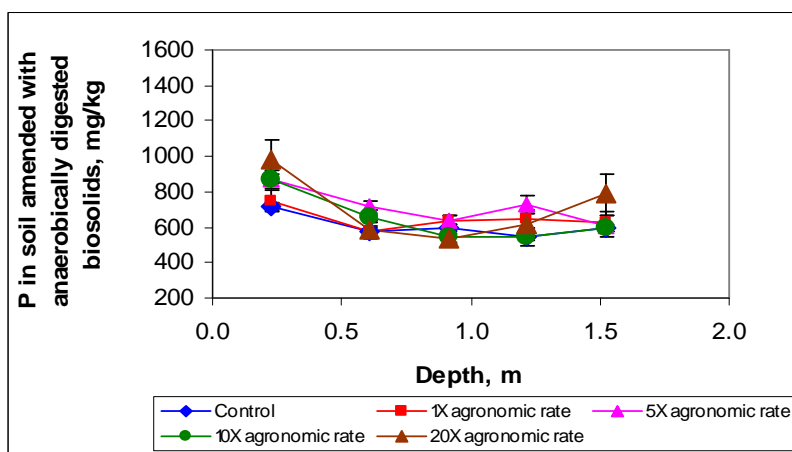
Table 28. Statistical analyses of total P in soil amended with anaerobically digested biosolids

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.4062	no	0.6243	no
	0.6	0.2581	no	0.9921	no
	0.9	0.9434	no	0.2342	no
	1.2	0.0058	higher	0.0654	no
	1.5	0.1256	no	0.3975	no
5X	0.2	0.4084	no	0.0071	higher
	0.6	0.8581	no	0.0048	higher
	0.9	0.6945	no	0.2354	no
	1.2	0.0076	higher	0.0024	higher
	1.5	0.0187	higher	0.7631	no
10X	0.2	0.3377	no	0.0015	higher
	0.6	0.949	no	0.104	no
	0.9	0.0717	no	0.3508	no
	1.2	0.078	no	0.9795	no
	1.5	0.7643	no	0.9376	no
20X	0.2	0.7997	no	0.0061	higher
	0.6	0.0853	no	0.7861	no
	0.9	0.0505	no	0.2295	no
	1.2	0.8737	no	0.1569	no
	1.5	0.1196	no	0.0339	higher



(a)

Figure 10. Total P from soil amended with anaerobically digested biosolids as (a) at the end of Year 1 and (b) at the end of Year 2. The error bars represent the standard errors based on variation of six subplots.



(b)

Figure 10. Continued.

Phosphorus Mass Balance

The P mass balance was conducted on the first 0.3 m of soil after biosolids were surface applied. For the first acre-foot, P-accumulation (kg/ha) was estimated using the P concentration (measured at a depth of 0.2 m) minus the P concentration in the control multiplied by the volume of soil. The P-accumulation was compared to the P-residual which was equal to the P applied (kg/ha) minus the P plant uptake (kg/ha) which was calculated by multiplying measured P concentration in plant tissue (mg/kg) and biomass yield (kg/ha). The P residual is equal to the difference between the amount of P applied and the P plant uptake. P plant uptake at lime-stabilized biosolids sites were negligible, however, the P accumulation were less than the amount of P residual at most biosolids loading rates (Tables 29-31). The most likely causes of this discrepancy were the assumption of soil homogeneity, dilution of surface P by biosolids application, the possibility of soil erosion (primarily through wind action) as well as potential deposition from dust storm.

Table 29. P mass balance in lime-stabilized biosolids-amended soil

Lime stabilized biosolids				
Multiple of agronomic rate	P applied (kg/ha)	Plant uptake (kg/ha)	P residual (kg/ha)	P accumulation (kg/ha)
1X	96.75	1.21	95.54	-59.40
5X	483.76	0.52	483.24	160.99
10X	967.53	0.41	967.12	661.57
20X	NA	NA	NA	NA

Table 30. P mass balance in aerobically digested biosolids-amended soil

Aerobically digested biosolids				
Multiple of agronomic rate	P applied (kg/ha)	Plant uptake (kg/ha)	P-residual (kg/ha)	P accumulation (kg/ha)
1X	165.46	1.25	164.21	33.49
5X	828.28	1.06	827.22	-29.92
10X	1656.56	1.48	1655.08	398.97
20X	3313.13	1.58	3311.55	621.91

Table 31. P mass balance in anaerobically digested biosolids-amended soil

Anaerobically digested biosolids				
Multiple of agronomic rate	P applied (kg/ha)	Plant uptake (kg/ha)	P - residual (kg/ha)	P accumulation (kg/ha)
1X	71.47	1.31	70.16	131.99
5X	357.34	1.18	356.16	515.94
10X	714.69	0.80	713.89	523.90
20X	1429.37	1.05	1428.32	878.20

Relationship Between Metals (Ca, Al, and Fe) and P Leachability

The availability of P in biosolids or biosolids-amended soils is governed by adsorption or precipitation reactions of inorganic P (Jenkins, Horwath, and Stutz-McDonald, 2000; McCoy, Sikora, and Weil, 1986; Chang et al., 1983; Taylor et al., 1978). It is also believed that P in biosolids or biosolids-amended soils is strongly associated with Al and Fe rather than Ca. Menar and Jenkins (1972) stated that the effect of Ca on immobilizing P in biosolids or biosolids-amended soils is not significant because the solubility of calcium phosphates decreases with pH below 10. To evaluate

the leachability/availability of P from various biosolids-amended soils in this study, the molar ratio of P to Al+Fe was used (Jenkins, Horwath, and Stutz-McDonald, 2000). P leachability is at low level if the molar ratio of P to Al+Fe is below 1. In other words, P leachability is controlled by aluminum/iron phosphates since the molar ratios of Fe to P and Al to P are 1 in these precipitates (Jenkins, Horwath, and Stutz-McDonald, 2000).

The results in Tables 32-34 show that P leachability from soils amended with lime-stabilized, aerobically digested, and anaerobically digested biosolids is low because all $[P]/([Al]+[Fe])$ ratios are below 1. This finding is important in terms of ground water quality protection because there is concern that biosolids application rate based on crop N requirement results in excess P applied to soils. As such high P concentrations (Figures 8-10) tend to remain on the soil surface (i.e., 0.2 m or 0.5 ft), there is still a possibility that P on soil surface may be lost through soil erosion (through overland moisture flow or wind).

To date, there has been no established relationship between Ca on P leachability from biosolids land application sites. However, Ca was expected to rapidly precipitate P given that the soil is alkaline and calcium phosphate ($Ca_3(PO_4)_2$) is highly insoluble ($K_{sp} = 2.07 \times 10^{-33}$). Statistical analyses (Tables 26-28) suggested that P accumulation occurred within the first 0.3 m of soil depth. In contrast, at lower soil depth (e.g. 1.5 m), P concentrations were not statistically different from the control. These findings were consistent with the assumed reactivity of P with soil Al, Fe, and Ca to form insoluble precipitates.

Table 32. [P]/[Al]+[Fe] in soil amended with lime-stabilized biosolids in Year 2

[P]/[Al]+[Fe]				
		Biosolids application rate (multiple of agronomic rate)		
Depth (m)	Control	1X	5X	10X
0.2	0.029	0.022	0.030	0.035
0.6	0.029	0.024	0.027	0.027
0.9	0.029	0.024	0.032	0.030
1.2	0.029	0.024	0.028	0.033
1.5	0.030	0.022	0.040	0.032

Table 33. [P]/[Al]+[Fe] in soil amended with aerobically digested biosolids in Year 2

[P]/[Al]+[Fe]					
		Biosolids application rate (multiple of agronomic rate)			
Depth (m)	Control	1X	5X	10X	20X
0.2	0.029	0.031	0.025	0.035	0.037
0.6	0.029	0.024	0.023	0.028	0.036
0.9	0.029	0.028	0.026	0.032	0.034
1.2	0.029	0.029	0.031	0.035	0.036
1.5	0.030	0.029	0.035	0.041	0.040

Table 34. [P]/[Al]+[Fe] in soil amended with anaerobically digested biosolids in Year 2

[P]/[Al]+[Fe]					
		Biosolids application rate (multiple of agronomic rate)			
Depth (m)	Control	1X	5X	10X	20X
0.2	0.029	0.028	0.033	0.032	0.041
0.6	0.029	0.029	0.029	0.029	0.028
0.9	0.029	0.022	0.026	0.033	0.032
1.2	0.029	0.023	0.029	0.032	0.032
1.5	0.030	0.025	0.029	0.030	0.042

Empirical Correlation Between P Loading Rate and P Accumulation

The following correlations were built using linear regression to plot P accumulation versus P applied (i.e. at 1X, 5X, 10X, and 20X agronomic rate) for each type of biosolids at 0.2 m depth (Figures 11-13). The resulting linear equations (R^2 values ranged from 0.87 to 0.97) suggested that P accumulation at the soil surface increases with increasing P application. Therefore, over the time scale of this study, biosolids land application should not cause problem in terms of P leachability.

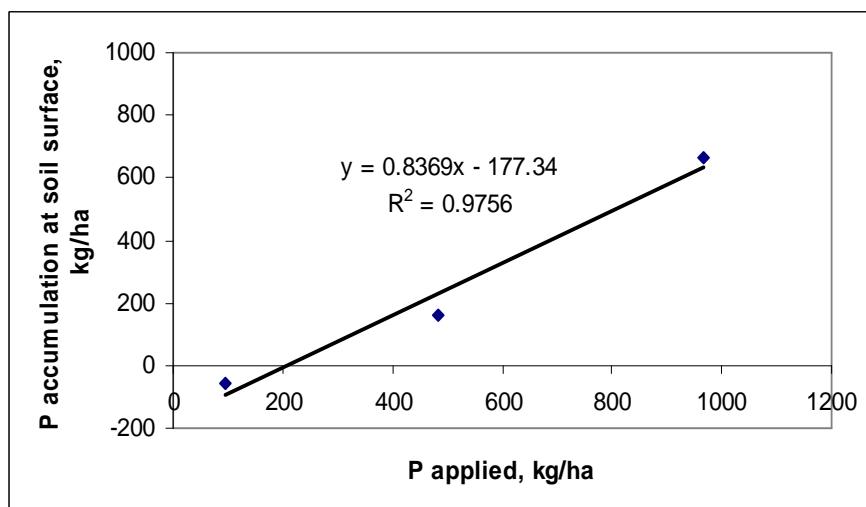


Figure 11. Correlation between P loading rate and P accumulation at the soil surface in lime-stabilized biosolids-amended sites.

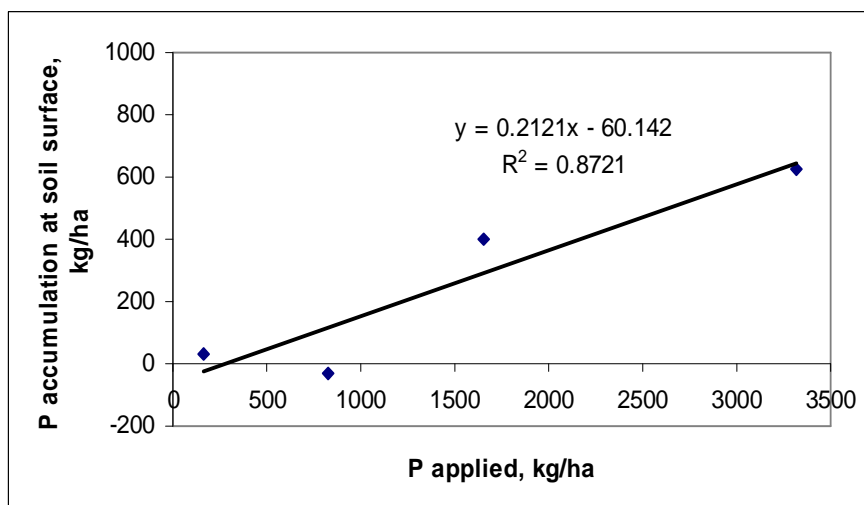


Figure 12. Correlation between P loading rate and P accumulation at the soil surface in aerobically digested biosolids-amended sites.

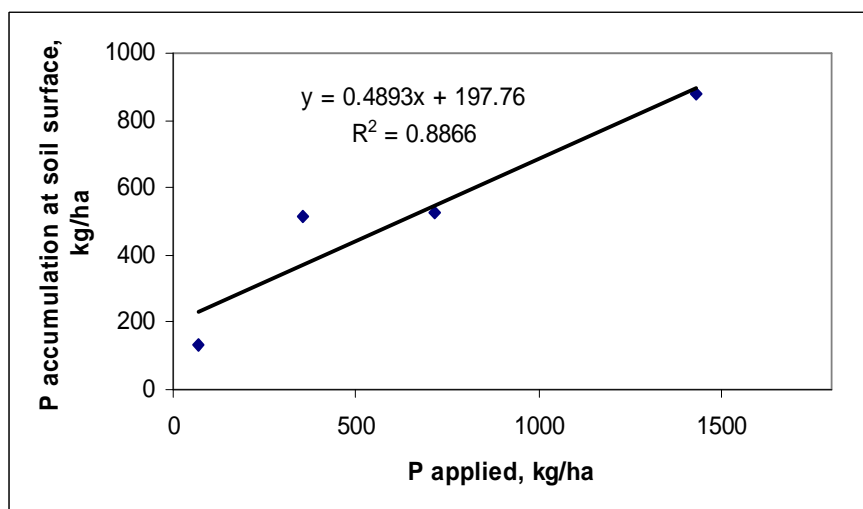


Figure 13. Correlation between P loading rate and P accumulation at the soil surface in anaerobically digested biosolids-amended sites.

Potential P Loss from Soil Erosion

Even though the molar ratios of total P to the total of Al and Fe were below 1 (i.e., low leachability of P at this study site), P may be also lost through soil erosion. Therefore, the universal soil loss equation (Eq. 8) presented in USDA (1998) was applied to obtain the soil loss in this study. It should be noted that the calculation of soil loss was relative since the universal soil loss equation is comprised of empirical factors.

$$A = R \times K \times LS \times C \times P \quad (8)$$

where:

A: soil loss, metric tons/yr

R: rainfall and runoff factor

K: soil erodibility factor

LS: slope length and gradient factor

C: cover and management factor

P: support practice factor

All parameters in the Eq. 8 were drawn from USDA (1998) based on the following facts including a) the study site did not have any tillage and irrigation, b) the soil has a slope of 5%, c) the slope length is long and linear, and d) the soil is sandy loam. Therefore, R, K, LS, C, and P were chosen as 10, 0.23, 0.6475, 0.005, and 0.25, respectively. The soil loss at the study site was calculated as followed:

$$A = 10 \times 0.23 \times 0.6475 \times 0.005 \times 0.25 = 0.00186 \text{ metric tons /ha-yr}$$

$$A = 1.86 \text{ kg/ha-yr}$$

The approximate soil loss at the study site is 1.86 kg per hectare per year. Hence, P loss through soil erosion is minimized in this study.

Plant Available P (Olsen P)

In general, the highest plant available P (Olsen P) concentrations were found in soil surface (0.2 m) in soil amended with lime-stabilized, aerobically digested, and anaerobically digested biosolids as seen in Figures 14-16, respectively. In a few cases, plant available P also increased with increasing biosolids application rates. As displayed in Tables 35-37, the statistical analyses did not demonstrate accumulations of plant available P at the depths of 0.6-1.5 m in all biosolids-amended test sites (i.e., 0.6, 0.9, 1.2, and 1.5 m). Moreover, the trend of plant available P in this study was similar to that reported in a previous study (Fitzpatrick et al., 2004). Statistical analyses are presented in Appendix F.

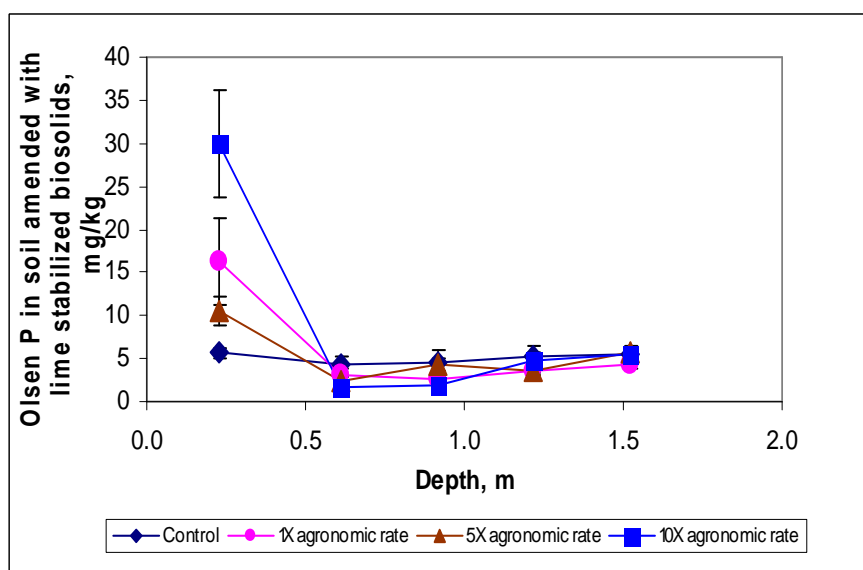


Figure 14. Olsen P from soil amended with lime-stabilized biosolids at the end of Year 2. The error bars represent the standard errors.

Table 35. Statistical analyses of Olsen P in soil amended with lime-stabilized biosolids at the end of Year 2

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
1X	0.2	0.0244	higher
	0.6	0.4451	no
	0.9	0.4026	no
	1.2	0.3497	no
	1.5	0.2151	no
5X	0.2	0.0066	higher
	0.6	0.2923	no
	0.9	0.9095	no
	1.2	0.3710	no
	1.5	0.7907	no
10X	0.2	<0.0001	higher
	0.6	0.1121	no
	0.9	0.2880	no
	1.2	0.7899	no
	1.5	0.9411	no

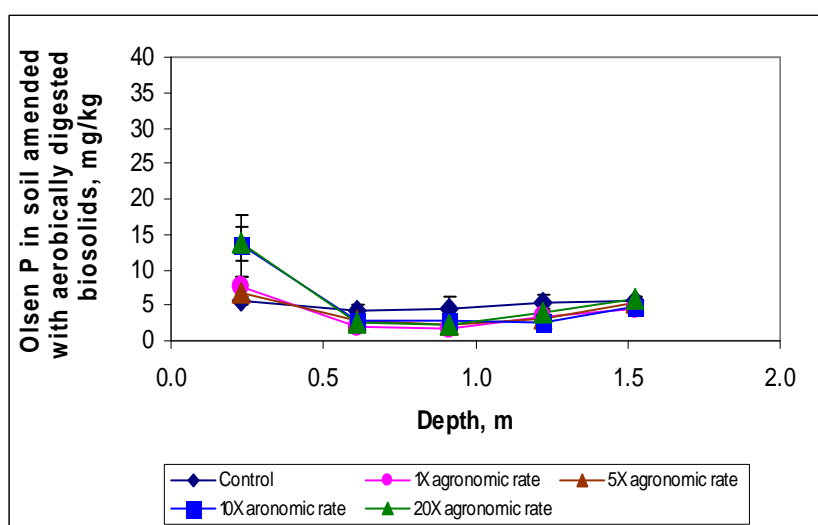


Figure 15. Olsen P from soil amended with aerobically digested biosolids at the end of Year 2. The error bars represent the standard errors based on variation of six subplots.

Table 36. Statistical analyses of Olsen P in soil amended with aerobically digested biosolids at the end of Year 2

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
1X	0.2	0.1938	no
	0.6	0.1424	no
	0.9	0.2428	no
	1.2	0.2832	no
	1.5	0.3210	no
5X	0.2	0.3134	no
	0.6	0.3682	no
	0.9	0.3089	no
	1.2	0.2287	no
	1.5	0.9248	no
10X	0.2	0.0103	higher
	0.6	0.4299	no
	0.9	0.4605	no
	1.2	0.1687	no
	1.5	0.5966	no
20X	0.2	0.0003	higher
	0.6	0.2421	no
	0.9	0.3228	no
	1.2	0.5031	no
	1.5	0.7302	no

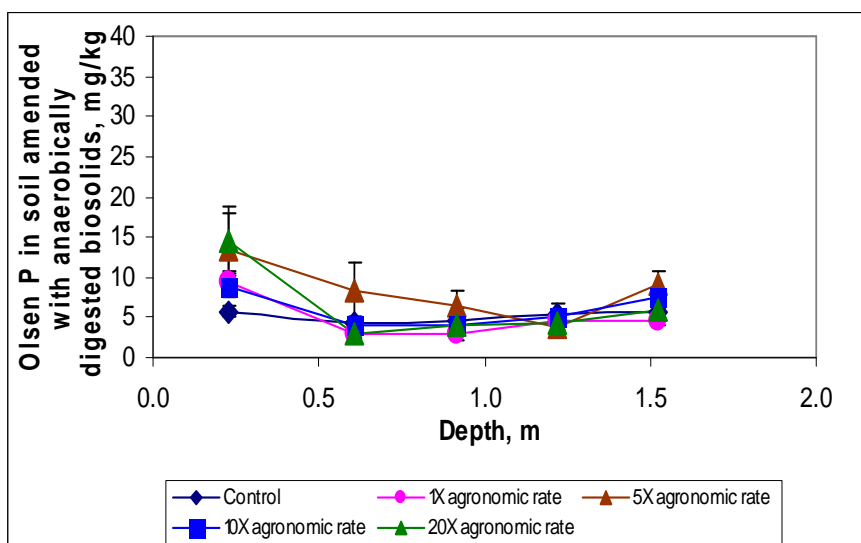


Figure 16. Olsen P from soil amended with anaerobically digested biosolids at the end of Year 2. The error bars represent the standard errors based on variation of six subplots.

Table 37. Statistical analyses of Olsen P in soil amended with anaerobically digested biosolids at the end of Year 2

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
1X	0.2	0.0065	higher
	0.6	0.3854	no
	0.9	0.4787	no
	1.2	0.6436	no
	1.5	0.3834	no
5X	0.2	0.0187	higher
	0.6	0.1421	no
	0.9	0.5500	no
	1.2	0.5447	no
	1.5	0.0292	higher
10X	0.2	0.0259	higher
	0.6	0.9073	no
	0.9	0.8608	no
	1.2	0.8476	no
	1.5	0.1037	no
20X	0.2	0.0126	higher
	0.6	0.3561	no
	0.9	0.8613	no
	1.2	0.6175	no
	1.5	0.7529	no

Adsorption and Desorption of Soil P

The most available inorganic form of P is orthophosphate which is likely adsorbed by iron hydroxide (Fe(OH)₃) in soil because iron hydroxide is naturally found in large quantities (Evangelou, 1998). The available orthophosphate fraction in total P was not determined in this study. However, assuming that any fraction of available orthophosphate would be adsorbed by Fe(OH)₃ or precipitated as FePO₄, there is the potential that desorption will also occur in which orthophosphate is released back to soils. This is possible because the reduction of Fe³⁺ to Fe²⁺ is a favorable reaction described in Eq. 2 with the oxidation potential of +0.771 V (Metcalf and Eddy, 2003).



Organic matter is probably the reducing agent for this reaction that occurs under saturated soil condition. Therefore, as the reaction in Eq. 2 proceeds to the right, sorbed P is released back to the soils. The released P is likely reacted with available Ca²⁺, Al³⁺ in soils to form calcium phosphate and aluminum phosphate, which is highly possible due to the extremely low solubility constants (K_{sp}) of calcium phosphate and aluminum phosphate. At the standard condition (i.e., 25⁰C), K_{sp} of calcium phosphate and aluminum phosphate are 2.07×10^{-33} and 9.84×10^{-21} , respectively, which indicates that calcium and aluminum phosphates are insoluble. Therefore, as soon as orthophosphate is desorbed, calcium and aluminum phosphates will be precipitated. As mentioned in chapter II, calcium phosphate is the most available form for plant uptake, thus it can refill the available inorganic P pool in soils. The adsorption/desorption and precipitation cycle of soil P can at least minimize P leaching to ground water due to the phosphate formation, which greatly influences the P balance in soil after biosolids amendments.

Biosolids Application Rate Based on Phosphorus

Due to the increased concern over eutrophication caused by excess P from N-based biosolids application, there is growing interest in basing the biosolids application rate on phosphorus instead of nitrogen. The equation for P-based biosolids application rate is presented in USEPA (1995) with the assumption that 50% of the inorganic P in biosolids is available for plant uptake (USDA, 1994). The equation is described as follows:

$$\text{Agronomic rate} \left(\frac{\text{ton}}{\text{acre}} \right) = \frac{P_{\text{req}}}{\text{crop - available } P_2O_5 \text{ per ton biosolids (dry basis)}} \quad (10)$$

where:

P_{req} : adjusted crop phosphorus fertilizer requirement, lb/acre

Crop - available P_2O_5 : total lb P_2O_5 per ton of biosolids (dry basis) multiplied by 0.5, lb/ton

Total lb of P_2O_5 per ton biosolids: lb of phosphorus in biosolids multiplied by 4.6, lb/ton

4.6 is the factor used to convert lb of P to lb of P_2O_5 - mass weight ratio $P_2O_5:P = 142 : 31$

The P-based biosolids application rates were calculated using Eq. 10 for the three types of biosolids used in this study. It is clear that the rangeland system would need additional nitrogen fertilization for healthy growth if biosolids were applied using the P-based application rate as demonstrated in Table 38. In addition, since biosolids are relatively rich in phosphorus, use of a P-based agronomic rate approach will result in a much larger land requirement for biosolids management. These technical concerns result in an increasing overall cost, which ultimately will be paid by the general public through increased wastewater fees (Brandt, Elliot, and O'Connor, 2004; Shoher and Sims, 2003).

Table 38. Comparison of N-based and P-based biosolids application rates (dry basis)

N-based Biosolids application rate			
Multiple of agronomic rate (metric ton/ha)	Lime-stabilized biosolids (metric ton/ha)	Aerobically digested biosolids (metric ton/ha)	Anaerobically digested biosolids (metric ton/ha)
1X	19.75	3.44	2.86
5X	98.73	17.22	14.29
10X	197.45	34.44	28.59
20X	NA	68.88	57.17
P-based Biosolids application rate			
Multiple of agronomic rate (metric ton/ha)	Lime-stabilized biosolids (metric ton/ha)	Aerobically digested biosolids (metric ton/ha)	Anaerobically digested biosolids (metric ton/ha)
1X	3.00	0.31	0.59
5X	15.00	1.53	2.94
10X	30.00	3.06	5.88
20X	60.00	6.11	11.76

Minimizing Nutrient Loss from Biosolids Land Application

Phosphorus loss from biosolids-amended sites has been a public concern as biosolids are applied to meet crop N requirements. The phosphorus loss can be higher if biosolids application occurs at rates that exceed estimated agronomic rate. Potential phosphorus loss at this study site was evaluated previously using the molar ratio $[P]/([Al]+[Fe])$. These molar ratios were well below 1 indicating that phosphorus loss from biosolids land application was very low.

Another approach, e.g., Phosphorus Site Index (PSI), can be used to determine the level of phosphorus movement from a site. The PSI, which takes into account site and transport characteristics along with source and management characteristics, was developed specifically for the state of Maryland to protect sensitive watersheds such as

the Chesapeake Bay (Coale, 2005). However, it is not currently a national approach. The site and transport characteristics are comprised of soil erosion, soil runoff class, subsurface drainage, leaching potential, and priority of receiving water. Each component except soil erosion is rated on a 0-8 scale where 0 represents very low level and 8 represents very high level using the information from the Tooele Soil Survey (USDA, 2000). Soil erosion loss (ton/acre) is obtained using the universal soil loss equation (Eq. 8). The total site and transport value is the sum of the component values multiplied by a scaling factor of 0.02. The source and management characteristics include soil test P, P fertilizer application rate, P fertilizer application method and timing, organic P application rate, and organic P application method and timing. The P fertilizer application method and timing and the organic P application method and timing are rated on a 0-60 scale depending on the application method and timing while the other components are represented in lb P₂O₅/acre multiplied by their respective factors from the PSI user guide (Coale, 2005). The total of the five component values is the source and management value.

Finally, the PSI value is the product of the total site and transport value and the source and management value. Thus, P loss rating is characterized using the PSI scale where low potential P movement is represented by PSI of 0-50 and very high P movement has PSI > 100. PSI values of medium and high P movements fall within the ranges of 51-75 and 76-100, respectively.

Based on the PSI values of the biosolids-amended test sites (Table 39), lime-stabilized biosolids may be applied only at the N-based agronomic rate in spite of a medium potential loss. At higher application rates, P loss at lime stabilized biosolids-

amended test treatments will be very high. Meanwhile, application rate up to ten times (10X) the N-based agronomic rate can be used for aerobically digested biosolids since P loss level range from low to medium. Anaerobically digested biosolids can be applied up to five times (5X) the N-based agronomic rate respective to potential P levels at these sites (low to medium).

It is clear that lime-stabilized biosolids exhibit higher potential P compared to the other types of biosolids when they are applied at the same biosolids application rates. This is not surprising since significantly higher amounts of lime-stabilized biosolids were applied to the test sites compared with those of aerobically digested and anaerobically digested biosolids due to low nutrient levels (i.e., N and P) found in lime-stabilized biosolids (Table 8). However, previous results of potential P leaching based on the molar ratio of $[P]/[Al]+[Fe]$ indicated that P loss at these biosolids-amended sites at up to twenty times (20X) the N-based agronomic rate was low. This finding agrees with the potential P loss determined by the PSI values because the excess P forms phosphate precipitates with calcium, aluminum and iron. At alkaline conditions, formation of calcium phosphate is high because of its relatively small solubility constant ($K_{sp} = 2.07 \times 10^{-33}$). These precipitates tend to remain immobile in soils due to their highly insolubility, and biosolids application at this study site was a one-time application.

Table 39. Phosphorus Site Index (PSI) of biosolids land application sites

Multiple of agronomic rate	Lime-stabilized biosolids		Aerobically digested biosolids		Anaerobically digested biosolids	
	PSI	Potential P loss	PSI	Potential P loss	PSI	Potential P loss
1X	74	Medium	25	Low	30	Low
5X	292	Very high	47	Low	73	Medium
10X	564	Very high	75	Medium	126	Very high
20X	NA	NA	130	Very high	233	Very high

CHAPTER VI
METALS IN BIOSOLIDS-AMENDED SOILS

Cadmium (Cd), lead (Pb), and molybdenum (Mo) concentrations in biosolids-amended soils are not presented here because they were below the detection limits (1.5, 2.5, and 2.5 mg/kg, respectively) in both Year 1 and Year 2. Metal levels in biosolids-amended soils were compared with the regulatory limits (Table 40). The cumulative loading rate is a regulatory derived value given in kg/ha. The regulation assumes that only the first 30.5 cm of soil depth (plow layer) is monitored. In addition, this is a large one-time biosolids application scenario not a continuous application. Given this management approach, metal concentration limits were derived from the regulatory required cumulative loading rates assigned for each of the regulated metals.

Arsenic (As) in Year 1 did not accumulate at soil surface in biosolids-amended test plots. Statistical analyses demonstrated levels of arsenic within soil surface were not

Table 40. Metal loading rate limits for land-applied biosolids[¶]

Metal	Cummulative loading rate limits	
	kg/ha	mg/kg [§]
As	41	9
Cd	39	9
Cu	1500	344
Pb	300	69
Mo	NA ^{§§}	NA ^{§§}
Ni	420	96
Se	100	23
Zn	2800	642

[¶]Adapted from USEPA (1995) and McFarland (2001)

[§]Converted to soil concentration assuming 30.5-cm depth and a bulk density of 1.43 g/cm³

^{§§}USEPA is re-examining the limit

different from the control (Tables 41-43). This arsenic behavior can be understood in light of the impact of phosphorus on arsenic mobility. It should be noted that arsenic exists as As(III) or As(V) in the soil environment and As(III) predominates in soil at increasing pH. Soil pH is a key factor on the adsorption of As(III) as a previous study showed that the maximum adsorption of As(III) by iron oxide was at pH 7 (Pierce and Moore, 1980). However, with high concentrations of phosphorus in biosolids, arsenic tends to become more mobile since phosphorus can displace arsenic on adsorption sites. This, at least in part, explains the lack of arsenic accumulation within the upper reaches of the soil column. As(III) is more leachable than As(V) due to its high solubility. However, As(III) could be oxidized to As(V) in the presence of manganese oxide serving as the primary electron acceptor. As compared to the control, arsenic concentrations in lime-stabilized and aerobically digested biosolids-amended soils were not statistically different from the control at various soil depths except at 1.5 m (Tables 41-42). In anaerobically digested biosolids-amended test sites, no arsenic accumulation was found except at the soil surface (0.2 m) at the 20X agronomic rate site (Table 43). Arsenic concentrations in all biosolids-amended soils were below the concentration limit (Table 40). Details about statistical analyses are summarized in Appendix G.

Copper (Cu) concentrations did not show a consistent trend among biosolids-amended test sites. Copper concentrations in biosolids-amended soils were found to be well below the concentration limit from the 40 CFR Part 503 rule (Table 40). Increasing copper concentrations from Year 1 to Year 2 were found in soils that had received lime-stabilized biosolids meanwhile the opposite trend existed in soils that had received

aerobically digested biosolids. In many cases, copper accumulation was found at 0.2 to 1.2 m depths (Tables 44-46). Statistical analyses are shown in Appendix H.

In most cases, nickel (Ni) exhibited a tendency to accumulate at the soil surface (0.2 m) (Tables 47-49). Nickel accumulation within the soil surface indicated nickel immobility under oxidizing conditions. Nickel concentrations decreased from Year 1 to Year 2 in all biosolids-amended soils, possibly indicative of plant uptake. Vasquez (2008) suggests that plant uptake of Ni occurred and that levels of Ni in plants in biosolids-amended sites were below the tolerable limits. Additionally, nickel is retained in soil through adsorption to iron and manganese oxides as well as organic matter (McLean and Bledsoe, 1992). Most nickel concentrations were below the cumulative loading rate limit. Nickel in soil that had received lime-stabilized biosolids at the loading rate equal to agronomic rate was higher than the concentration limit in Year 1. Refer to Appendix I for details about statistical analyses.

Soil amended with lime-stabilized biosolids had lower selenium (Se) level than those in soils amended with aerobically digested biosolids at low biosolids loading rates (1X and 5X) in Year 1 (Tables 50-52). However, due to high soil pH, selenium in the test treatments with lime-stabilized biosolids amendment can be more mobile than selenium in the test treatments with aerobically digested biosolids amendments. Within the soil surface (0.2 m), statistical analyses suggested that selenium did not accumulate in the biosolids-amended test sites, which suggests significant selenium mobility associated with high soil pH and oxidizing conditions. In addition, the elevated concentrations of phosphorus (P) in biosolids added through land application could enhance selenium mobility since phosphorus, especially phosphate, strongly adsorbs to soils and displaces

selenium. In general, selenium in biosolids-amended soils was well below the concentration limit from the 40 CFR Part 503 rule. Statistical analyses are reported in Appendix J.

Zinc (Zn) exhibited a similar tendency as copper (Cu) in all biosolids-amended soils. In some cases, zinc was also found to accumulate at soil surface in both Year 1 and Year 2 following biosolids land application. Additionally, zinc was found to accumulate at depths of 0.6-1.2 m in both years based on statistical analyses (Tables 53-55). However, zinc concentrations were well below the concentration limit (Table 40). High soil pH in biosolids-amended rangelands is favorable for Zn adsorption. Also, hydrolyzed species of zinc, which occurs at $\text{pH} > 7.7$, are strongly adsorbed to the soil surface (McLean and Bledsoe, 1992). Refer to Appendix K for statistical analysis reports.

There was no trend for all metals (As, Cu, Ni, Zn, and Se) in biosolids-amended soils at the end of Year 1 and Year 2 following biosolids application. This was not surprising given the impact on localized environmental conditions on metal mobility and leaching. The concentrations of metals in this work were below the concentration limits from the 40 CFR Part 503 rule for biosolids-amended soils (Table 40). This may be explained by the fact that metals in biosolids are regulated before they could be land applied (Table 5). Other research (Vasquez, 2008) suggests that levels of metal in plants at this study site were well below the plant tolerable limits. Thus, biosolids application in this study did not pose any risk to human health, animals, or the environment with respect to potential metal accumulation. The study site should be safe for future cattle grazing since this was the goal of applying biosolids to this disturbed rangeland.

Table 41. Statistical analyses of arsenic (As) in lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
1X	0.2	0.5113	no
	0.6	0.1804	no
	0.9	0.4393	no
	1.2	0.7742	no
	1.5	0.0007	lower
5X	0.2	0.3472	no
	0.6	0.8155	no
	0.9	0.8801	no
	1.2	0.3645	no
	1.5	0.0011	lower
10X	0.2	0.6705	no
	0.6	0.7306	no
	0.9	0.6419	no
	1.2	0.6543	no
	1.5	0.0074	lower

Table 42. Statistical analyses of arsenic (As) in aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
1X	0.2	0.4208	no
	0.6	0.0468	lower
	0.9	0.1750	no
	1.2	0.4105	no
	1.5	0.0021	lower
5X	0.2	0.2488	no
	0.6	0.1992	no
	0.9	0.4844	no
	1.2	0.5463	no
	1.5	0.0012	lower
10X	0.2	0.2289	no
	0.6	0.2043	no
	0.9	0.1467	no
	1.2	0.3732	no
	1.5	0.0005	lower
20X	0.2	0.9640	no
	0.6	0.1955	no
	0.9	0.7488	no
	1.2	0.6807	no
	1.5	0.0017	lower

Table 43. Statistical analyses of arsenic (As) in anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
1X	0.2	0.9035	no
	0.6	0.1756	no
	0.9	0.1271	no
	1.2	0.7800	no
	1.5	0.3471	no
5X	0.2	0.3524	no
	0.6	0.3812	no
	0.9	0.1499	no
	1.2	0.1463	no
	1.5	0.3706	no
10X	0.2	0.1536	no
	0.6	0.0852	no
	0.9	0.8092	no
	1.2	0.1198	no
	1.5	0.4015	no
20X	0.2	0.0088	higher
	0.6	0.1063	no
	0.9	0.3127	no
	1.2	0.0645	no
	1.5	0.4065	no

Table 44. Statistical analyses of copper (Cu) in lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.3614	no	0.2543	no
	0.6	0.8046	no	0.1573	no
	0.9	0.3503	no	0.6169	no
	1.2	0.4731	no	0.1911	no
	1.5	0.7027	no	0.1089	no
5X	0.2	0.016	lower	0.0007	lower
	0.6	0.0985	no	0.107	no
	0.9	0.3909	no	0.1778	no
	1.2	0.2206	no	0.0019	lower
	1.5	0.3888	no	0.0112	lower
10X	0.2	0.9688	no	NA	NA
	0.6	0.386	no	<0.0001	lower
	0.9	0.9149	no	<0.0001	lower
	1.2	0.9344	no	<0.0001	lower
	1.5	0.6305	no	0.0421	lower

Table 45. Statistical analyses of copper (Cu) in aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.2728	no	NA	NA
	0.6	0.1969	no	NA	NA
	0.9	0.1342	no	NA	NA
	1.2	0.6474	no	NA	NA
	1.5	0.2635	no	NA	NA
5X	0.2	0.3145	no	NA	NA
	0.6	0.9401	no	NA	NA
	0.9	0.029	higher	0.0007	lower
	1.2	0.132	no	<0.0001	lower
	1.5	0.5829	no	NA	NA
10X	0.2	0.2308	no	0.9158	no
	0.6	0.0003	higher	0.2326	no
	0.9	0.0019	higher	0.0285	lower
	1.2	0.0042	higher	0.0015	lower
	1.5	0.0211	higher	NA	NA
20X	0.2	0.0007	higher	NA	NA
	0.6	0.0103	higher	NA	NA
	0.9	0.0307	higher	NA	NA
	1.2	0.0951	no	0.0125	lower
	1.5	0.2491	no	0.0124	lower

Table 46. Statistical analyses of copper (Cu) in anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.3669	no	NA	NA
	0.6	0.0008	no	0.0078	lower
	0.9	0.9823	no	0.6389	no
	1.2	0.1072	no	0.3141	no
	1.5	0.0728	no	0.0529	no
5X	0.2	0.8211	no	0.4825	no
	0.6	0.0245	no	0.3786	no
	0.9	0.4181	no	0.9132	no
	1.2	0.0341	no	0.1847	no
	1.5	0.3887	no	0.7502	no
10X	0.2	0.2862	no	<0.0001	lower
	0.6	0.3391	no	0.1027	no
	0.9	0.5175	no	0.0736	no

Table 46. Continued

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control	P-value	Statistically different from the control
10X	1.2	0.8175	no	<0.0001	lower
	1.5	0.5644	no	0.012	lower
20X	0.2	0.9335	higher	NA	NA
	0.6	0.0113	no	NA	NA
	0.9	0.6728	no	NA	NA
	1.2	0.0998	no	NA	NA
	1.5	0.3604	no	NA	NA

Table 47. Statistical analyses of nickel (Ni) in lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.8742	no	0.691	no
	0.6	0.6132	no	0.1254	no
	0.9	0.7991	no	0.0056	lower
	1.2	0.0581	no	0.5393	no
	1.5	0.9841	no	0.4693	no
5X	0.2	0.0044	lower	0.0015	lower
	0.6	0.1331	no	0.0023	lower
	0.9	0.5876	no	<0.0001	lower
	1.2	0.0138	lower	<0.0001	lower
	1.5	0.3344	no	<0.0001	lower
10X	0.2	0.0288	lower	0.0454	lower
	0.6	0.0977	no	0.0215	lower
	0.9	0.0818	no	0.02	lower
	1.2	0.0112	lower	0.0041	lower
	1.5	0.1092	no	0.2273	no

Table 48. Statistical analyses of nickel (Ni) in aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.0023	lower	0.2236	no
	0.6	0.0077	lower	0.0546	no
	0.9	0.7313	no	0.0077	lower
	1.2	0.4268	no	0.0145	lower
	1.5	0.0088	lower	0.5846	no
5X	0.2	0.4089	no	0.0079	lower
	0.6	0.0762	no	0.0043	lower

Table 48. Continued

		Year 1		Year 2	
Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control	P-value	Statistically different from the control
5X	0.9	0.7087	no	0.0001	lower
	1.2	0.1873	no	<0.0001	lower
	1.5	0.0118	lower	NA	NA
10X	0.2	0.0429	lower	0.0448	lower
	0.6	0.0051	lower	0.5301	no
	0.9	0.0029	lower	0.0393	lower
	1.2	0.5655	no	0.1422	no
	1.5	0.0024	lower	0.0004	lower
20X	0.2	0.0309	lower	0.1336	no
	0.6	0.0677	no	0.129	no
	0.9	0.9937	no	0.0134	lower
	1.2	0.0986	no	<0.0001	lower
	1.5	0.4966	no	NA	NA

Table 49. Statistical analyses of nickel (Ni) in anaerobically digested biosolids-amended soil

		Year 1		Year 2	
Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.1122	no	0.4932	no
	0.6	0.0006	lower	0.0189	lower
	0.9	0.6333	no	0.8856	no
	1.2	0.7607	no	0.0341	lower
	1.5	0.0012	lower	0.0051	lower
5X	0.2	0.0156	lower	NA	NA
	0.6	0.0351	lower	NA	NA
	0.9	0.6629	no	NA	NA
	1.2	0.5846	no	NA	NA
	1.5	0.0014	lower	NA	NA
10X	0.2	0.0094	lower	NA	NA
	0.6	0.0147	lower	NA	NA
	0.9	0.2462	no	NA	NA
	1.2	0.5203	no	NA	NA
	1.5	<0.0001	lower	NA	NA
20X	0.2	0.3919	no	NA	NA
	0.6	0.0027	lower	NA	NA
	0.9	0.5765	no	NA	NA
	1.2	0.6718	no	NA	NA
	1.5	0.0003	lower	NA	NA

Table 50. Statistical analyses of selenium (Se) in lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
1X	0.2	NA	NA
	0.6	NA	NA
	0.9	0.1698	no
	1.2	0.1223	no
	1.5	0.0461	lower
5X	0.2	0.5927	no
	0.6	NA	NA
	0.9	0.6031	no
	1.2	0.4901	no
	1.5	0.2281	no
10X	0.2	0.1633	no
	0.6	0.382	no
	0.9	0.5961	no
	1.2	0.2427	no
	1.5	0.5362	no

Table 51. Statistical analyses of selenium (Se) in aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
1X	0.2	0.4243	no
	0.6	0.3605	no
	0.9	0.3914	no
	1.2	0.9954	no
	1.5	0.1484	no
5X	0.2	0.2292	no
	0.6	0.3753	no
	0.9	0.2519	no
	1.2	0.1435	no
	1.5	0.9378	no
10X	0.2	0.1835	no
	0.6	0.3827	no
	0.9	0.3977	no
	1.2	0.0423	higher
	1.5	0.8708	no
20X	0.2	0.8167	no
	0.6	0.3814	no
	0.9	0.884	no
	1.2	0.744	no
	1.5	0.586	no

Table 52. Statistical analyses of selenium (Se) in anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control
1X	0.2	0.2836	no
	0.6	0.9062	no
	0.9	0.4883	no
	1.2	0.6169	no
	1.5	0.0079	lower
5X	0.2	0.7338	no
	0.6	0.4807	no
	0.9	0.105	no
	1.2	0.1222	no
	1.5	0.3875	no
10X	0.2	0.4802	no
	0.6	0.4576	no
	0.9	0.7759	no
	1.2	0.3294	no
	1.5	0.534	no
20X	0.2	0.0821	no
	0.6	0.2092	no
	0.9	0.0492	higher
	1.2	0.0449	higher
	1.5	0.4522	no

Table 53. Statistical analyses of zinc (Zn) in lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1		Year 2	
		P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.1748	no	0.0618	no
	0.6	0.4042	no	<0.0001	higher
	0.9	0.1333	no	0.0005	higher
	1.2	0.845	no	<0.0001	higher
	1.5	0.4838	no	0.0502	no
5X	0.2	0.3498	no	0.3681	no
	0.6	0.8913	no	0.2848	no
	0.9	0.4725	no	0.0746	no
	1.2	0.0144	higher	0.0226	higher
	1.5	0.8193	no	0.5948	no
10X	0.2	0.0222	higher	0.0489	lower
	0.6	0.6989	no	0.5101	no
	0.9	0.3468	no	0.5751	no
	1.2	0.3582	no	0.0163	lower

Table 53. Continued

		Year 1		Year 2	
Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control	P-value	Statistically different from the control
10X	1.5	0.5608	no	0.0418	lower

Table 54. Statistical analyses of zinc (Zn) in aerobically digested biosolids-amended soil

		Year 1		Year 2	
Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.3119	no	0.0002	lower
	0.6	0.0052	lower	0.0003	lower
	0.9	0.7309	no	0.0014	lower
	1.2	0.0533	no	0.5943	no
	1.5	0.0415	higher	0.0046	lower
5X	0.2	0.1446	no	0.8291	no
	0.6	0.0759	no	0.8747	no
	0.9	0.1873	no	0.6647	no
	1.2	0.0192	higher	0.003	higher
	1.5	0.6985	no	0.0167	lower
10X	0.2	0.6262	no	0.3586	no
	0.6	0.8964	no	0.5941	no
	0.9	0.8871	no	0.4456	no
	1.2	0.0022	higher	0.4445	no
	1.5	0.4991	no	<0.0001	lower
20X	0.2	0.0904	no	0.251	no
	0.6	0.2846	no	0.2405	no
	0.9	0.4503	no	0.3763	no
	1.2	0.2574	no	0.0861	no
	1.5	0.3995	no	<0.0001	lower

Table 55. Statistical analyses of zinc (Zn) in anaerobically digested biosolids-amended soil

		Year 1		Year 2	
Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control	P-value	Statistically different from the control
1X	0.2	0.2351	no	0.2934	no
	0.6	0.0007	lower	0.0971	no
	0.9	0.4761	no	0.899	no
	1.2	0.0621	no	0.077	no
	1.5	0.9402	no	0.5774	no
5X	0.2	0.9454	no	0.5329	no
	0.6	0.7263	no	0.7375	no

Table 55. Continued

		Year 1		Year 2	
Multiple of agronomic rate	Depth (m)	P-value	Statistically different from the control	P-value	Statistically different from the control
5X	0.9	0.7596	no	0.8228	no
	1.2	0.0136	higher	0.3692	no
	1.5	0.2456	no	0.0422	lower
10X	0.2	0.125	no	0.1636	no
	0.6	0.2236	no	0.9471	no
	0.9	0.0412	lower	0.0011	lower
	1.2	0.0132	higher	0.0049	lower
	1.5	0.0576	no	0.0019	lower
20X	0.2	1	no	0.3735	no
	0.6	0.0275	lower	0.0002	lower
	0.9	0.0557	no	NA	NA
	1.2	0.2007	no	NA	NA
	1.5	0.8027	no	NA	NA

CHAPTER VII

CONCLUSIONS AND ENGINEERING SIGNIFICANCE

Conclusions

Soil pH remained unchanged after biosolids land application, which could likely be due to the presence of carbonate in large quantities in soils. Electrical conductivity (EC) also did not change in most biosolids-amended sites. In some cases, EC was higher than the control, which could be attributed to low precipitation that helped preventing salt content from leaching. Many biosolids-amended sites were found to have low $\text{NH}_4\text{-N}$ and high $\text{NO}_3\text{-N}$ within the soil surface (0.2 m) compared with the control, which may have been the result of ammonia volatilization and nitrification. Due to high soil pH, high ambient temperature and low precipitation, volatilization of ammonia was favorable at the study site. Meanwhile, nitrification was enhanced by well-drained soil condition (i.e., aerobic condition). The high $\text{NO}_3\text{-N}$ levels were also due to the historical use of the site as an animal feeding and holding area since the $\text{NO}_3\text{-N}$ concentrations in the soil background was found as high as 156 mg/kg. The potential ground water source may not be affected due to the following reasons including a) the potential ground-water source is 24 m below ground surface, b) the quality of the potential ground-water source is considered poor, and c) evapotranspiration is much greater than precipitation at the study site and d) nitrate is likely lost as nitrogen gas through the denitrification process. The nitrogen balance at biosolids-amended sites was conducted within the soil surface using total N concentrations. Significant differences between the amount of N residual and N accumulation existed at all biosolids loading rates. The most likely reasons for the

discrepancies could be wind erosion, greater ammonia volatilization than predicted, soil heterogeneity and atmospheric deposition.

The Root Zone Water Quality Model (RZWQM) simulation results were not consistent with the field study results. The simulation had to use most of the default parameters for a typical agricultural cropping system from the RZWQM, which resulted in inadequate prediction of nitrogen (e.g. $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$) storage at various soil depths in biosolids-amended rangelands. For appropriate simulation, the model needs to be modified specifically for rangeland systems.

Cheatgrass, mouse barley, and hornseed buttercup were dominant plant species at the biosolids-amended sites. Even though these species are invasive, their dominance can still benefit the disturbed rangelands by a) reducing soil erosion, b) increasing phosphorus retention, c) enhancing soil drainage, and d) improving forage productivity.

Total P accumulated within the soil surface (0.2 m) in many of biosolids-amended sites, an observation that could be attributed to the formation of phosphate precipitates at the soil surface. In addition, P accumulation within the soil surface increases with increasing P loading rate. Phosphorus leaching was minimal based on its potential reactions with calcium (Ca) and the molar ratios of total phosphorus to the total of aluminum (Al) and iron (Fe). Calcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$) is favorable in alkaline condition and extremely insoluble ($K_{\text{sp}} = 2.07 \times 10^{-33}$). The $[\text{P}]/([\text{Al}]+[\text{Fe}])$ ratios were well below 1, which indicated low phosphorus leachability. It should be noted that a molar ratio higher than 1 indicates high phosphorus leachability.

The Phosphorus Site Index (PSI) was also used to evaluate phosphorus leachability from biosolids-amended sites. Lime-stabilized biosolids should be land

applied at rates that do not exceed the N-based agronomic rate because of potential phosphorus loss compared with other types of biosolids (e.g., aerobically digested and anaerobically digested biosolids). From a phosphorus control standpoint, aerobically digested biosolids may be best as they can be applied up to ten times (10 X) agronomic rate with only a medium potential phosphorus loss.

Plant available phosphorus (Olsen P) showed accumulation at the soil surface in biosolids-amended test plots, which was beneficial for plants in terms of nutrient uptake. Downward movement of plant available P in soils was not found, which helped minimize phosphorus leachability to ground water from biosolids-amended sites. It is recommended that total P and plant available P soil samples continue to be taken in the next two or three years for a completely compiled P data set from the one-time biosolids land application. The amount of P residual and P accumulation at the soil surface was significantly different at all biosolids application rates, which may be due to wind erosion, dilution effects from biosolids, soil heterogeneity, and external deposition.

P-based agronomic rates were significantly lower than the N-based agronomic rate, which leads to an increasing overall cost due to additional nitrogen fertilization and much larger land needed. However, in terms of regulatory limitations to biosolids land application, to date, biosolids must be applied using the N-based agronomic rate – except where a disturbed site is being restored.

The results from this study confirm that biosolids land application is safe in terms of regulated metal accumulation as specified under 40 CFR Part 503 Rule. Cadmium (Cd), lead (Pb), and molybdenum (Mo) were all below their detection limits in the test sites that had received biosolids at various application rates. The other five metals (As,

Cu, Ni, Se, and Zn) were well below the standard limits. Overall, metal concentrations in biosolids-amended soils did not exceed the regulated limits.

In summary, the large variability in the field data can be attributed to complex chemical and biological activities within the soil. With the time and financial constraints, the field sampling activity was designed with a pseudo replication approach. Nevertheless, N, P, and regulated metal concentrations in biosolids-amended test plots did not likely threaten human health and the surrounding environment from the one-time biosolids land application.

Engineering Significance

A previous study on this site (Desai, 2006) was conducted only on nitrogen mobility; therefore, this study was more comprehensive in terms of its focus on nutrient mobility from biosolids application including nitrogen, phosphorus, and regulated metals from biosolids land application in disturbed rangelands in western Utah. Moreover, this is the first time that phosphorus mobility in biosolids-amended rangelands has been studied. The study suggested that phosphorus should not cause a problem from one-time biosolids land application using N-based application rates. However, to adequately ensure that surface accumulated phosphorus is not mobilized by overland moisture flow and/or wind erosion, engineering controls would have to be considered as part of any biosolids land application design. For example, elimination of excessive slopes on the land application sites through grading and/or the installation of catch basins or berms may be necessary to minimize problems associated with overland moisture flow. Also, the establishment of an

adequate vegetative cover will be a key goal to mitigate concerns regarding the transport of phosphorus through wind erosion.

As shown in chapter IV, nitrate ($\text{NO}_3\text{-N}$) storage below the root zone at the biosolids application sites increases with increasing soil depth. This observation means that nitrate has potential to leach deeply into the soil. Therefore, biosolids application rates should be limited to the agronomic rate. Otherwise, other practical management practices to reduce nutrient loss, e.g., nitrogen and phosphorus, by surface runoff and subsurface flow need to be implemented if biosolids application rates exceed the agronomic rate.

Lime-stabilized biosolids should be only applied at the N-based agronomic rate while anaerobically digested biosolids can be applied up to ten times (10X) agronomic rate based on the PSI values to avoid excessive phosphorous losses. This will also minimize nitrate leaching below the root zone. Aerobically digested biosolids may be the best biosolids when they can be applied one (1X) to ten times (10X) agronomic rate since the P loss from these biosolids range from low to medium PSI levels. All management practices as stated previously to reduce nutrient loss at biosolids-amended sites should be considered as part of biosolids application design.

Nitrogen (i.e., $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$) simulation in biosolids-amended soils has been tested for the first time using the Root Zone Water Quality Model, but the RZWQM was inadequate for simulating these conditions. Therefore, a unique model to predict nutrient movements (i.e., N and P) in soil systems with biosolids amendment is needed. The model should be capable of predicting fate of nutrients in biosolids-amended soils for

long terms (e.g., 10-30 years after biosolids application), which will be especially meaningful for long-term application of biosolids.

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APPENDICES

Appendix A. Statistical analyses of pH in biosolids-amended soil

A.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	8.45	6.25	0.98	8.56	3.34	9.30
	0.6	8.62	3.50	10.27	8.68	4.75	1.09
	0.9	8.66	1.27	267.26	8.64	7.73	0.11
	1.2	8.51	1.08	323.52	8.18	5.61	0.06
	1.5	8.09	4.54	4.69	7.99	3.48	0.02
5X	0.2	8.66	6.54	0.00	8.64	3.15	1.78
	0.6	8.64	3.61	10.30	8.53	4.00	1.98
	0.9	8.04	3.61	0.94	8.26	5.14	4.15
	1.2	7.85	1.02	0.13	8.05	4.21	4.22
	1.5	7.77	1.15	0.00	7.88	1.76	18.96
10X	0.2	8.65	5.95	0.00	8.52	3.26	14.60
	0.6	8.65	5.36	4.88	8.51	4.23	2.96
	0.9	8.04	1.46	5.43	8.23	5.13	5.47
	1.2	7.88	0.72	3.24	8.05	4.11	4.24
	1.5	7.79	0.15	24.50	7.90	1.59	17.12

A.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	8.55	6.29	0.27	8.54	3.39	11.40
	0.6	8.58	4.61	4.69	8.70	5.23	1.46
	0.9	8.23	5.45	2.87	8.47	6.18	0.65
	1.2	8.01	4.42	1.44	8.19	5.25	0.08
	1.5	7.86	1.90	2.42	7.96	3.10	0.26
5X	0.2	8.78	5.84	0.32	8.61	4.50	1.90
	0.6	8.32	3.56	0.50	8.45	4.00	8.78
	0.9	8.03	1.68	3.98	8.30	5.74	1.68
	1.2	7.86	0.85	0.45	8.07	4.79	1.96
	1.5	7.77	0.97	0.05	7.89	1.69	17.69
10X	0.2	8.54	7.28	0.25	8.57	3.54	7.03
	0.6	8.32	3.51	0.61	8.47	4.19	6.16
	0.9	8.00	1.68	2.13	8.22	5.12	6.45
	1.2	7.85	1.14	0.07	8.03	4.27	6.37
	1.5	7.78	0.52	0.37	7.88	1.69	26.93
20X	0.2	8.43	6.63	1.09	8.65	3.57	1.08
	0.6	8.26	4.34	0.03	8.58	5.22	0.19
	0.9	7.99	2.09	0.91	8.26	5.46	3.66
	1.2	7.87	3.09	0.12	8.05	4.40	3.78
	1.5	7.76	1.50	0.00	7.90	1.71	12.83

A.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	8.56	6.71	0.21	8.56	3.63	7.36
	0.6	8.38	3.48	1.62	8.49	3.91	4.62
	0.9	8.19	4.42	3.21	8.23	5.12	5.54
	1.2	7.90	1.17	2.39	8.04	4.13	5.00
	1.5	7.82	0.78	5.12	7.89	1.62	19.73
5X	0.2	8.48	6.39	0.69	8.58	3.33	6.24
	0.6	8.28	3.52	0.20	8.60	5.16	0.02
	0.9	7.99	1.73	1.40	8.30	5.32	1.94
	1.2	7.88	1.82	0.43	8.08	4.27	2.46
	1.5	7.75	0.36	1.39	7.90	1.80	11.72
10X	0.2	8.45	6.60	0.92	8.60	3.71	3.34
	0.6	8.34	5.34	0.33	8.49	4.86	2.98
	0.9	8.10	6.07	0.76	8.29	6.01	1.64
	1.2	7.89	1.89	0.63	8.08	4.33	2.12
	1.5	7.77	1.01	0.01	7.91	1.60	11.93
20X	0.2	8.64	6.42	0.01	8.53	3.94	8.72
	0.6	8.30	3.40	0.41	8.53	4.10	2.06
	0.9	8.02	1.30	5.18	8.31	5.57	1.37
	1.2	7.90	1.02	3.36	8.07	4.41	2.37
	1.5	7.85	0.45	31.14	7.91	2.41	5.73

Appendix B. Statistical analyses of EC (dS/m) in biosolids-amended soil

B.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	1.50	21.74	22.49	1.89	146.35	0.63
	0.6	6.85	72.56	8.50	13.73	94.18	2.82
	0.9	21.59	54.72	17.75	21.59	57.12	8.73
	1.2	22.52	37.05	35.55	25.78	44.41	6.11
	1.5	26.06	39.21	17.21	29.72	34.41	10.05
5X	0.2	3.03	31.07	5.54	2.67	107.44	0.76
	0.6	13.40	46.99	0.06	21.74	58.29	4.33
	0.9	42.35	35.11	0.01	30.96	35.86	3.20
	1.2	44.83	18.87	0.34	34.30	27.10	6.06
	1.5	45.05	28.06	0.11	38.37	19.10	7.06
10X	0.2	2.87	36.70	2.99	3.21	92.40	3.75
	0.6	12.73	90.72	0.00	21.86	57.48	4.64
	0.9	38.87	32.69	0.34	31.78	35.63	4.77
	1.2	44.98	19.20	0.37	33.62	28.75	3.78
	1.5	48.63	17.95	2.18	37.23	19.57	3.00

B.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	1.78	33.01	2.09	3.34	93.86	4.32
	0.6	10.88	86.66	0.24	13.36	97.08	3.41
	0.9	32.07	58.02	1.67	22.58	56.67	5.66
	1.2	35.66	47.11	1.09	25.81	42.57	6.53
	1.5	35.84	45.50	1.28	30.61	36.81	5.78
5X	0.2	3.09	29.11	6.90	2.96	111.67	1.66
	0.6	20.70	36.17	6.73	25.03	53.38	11.89
	0.9	41.77	29.02	0.00	32.74	39.52	5.56
	1.2	47.55	18.05	1.81	34.13	37.44	2.92
	1.5	47.55	21.21	1.03	36.11	22.21	0.54
10X	0.2	2.30	28.47	0.43	3.28	105.41	3.18
	0.6	15.96	48.46	1.02	21.86	62.44	3.93
	0.9	40.70	32.85	0.05	33.54	33.49	9.89
	1.2	45.12	20.29	0.37	36.69	25.96	17.28
	1.5	45.70	20.54	0.37	38.54	19.02	8.86
20X	0.2	2.62	25.24	3.30	2.30	120.94	0.01
	0.6	13.75	40.60	0.19	21.07	70.77	2.24
	0.9	39.73	32.12	0.17	33.44	43.63	5.66
	1.2	43.02	35.11	0.00	35.90	29.47	9.41
	1.5	45.38	23.15	0.22	38.44	26.38	3.84

B.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	6.53	116.18	0.04	1.89	144.97	0.65
	0.6	18.28	36.09	19.48	20.66	66.80	2.07
	0.9	29.37	46.98	2.33	32.30	37.47	5.31
	1.2	34.23	30.89	0.04	34.52	28.02	6.24
	1.5	39.12	14.57	1.17	38.88	18.80	9.49
5X	0.2	7.22	77.40	0.35	2.70	109.57	0.81
	0.6	25.53	27.32	2.65	18.12	80.04	0.10
	0.9	32.20	22.02	3.97	28.94	45.77	0.34
	1.2	33.37	32.41	0.15	33.36	31.01	3.15
	1.5	39.65	22.75	0.29	36.98	25.13	1.43
10X	0.2	5.98	69.88	0.00	3.09	94.96	2.94
	0.6	26.93	52.74	0.31	20.70	75.91	1.63
	0.9	31.81	48.11	0.97	28.04	51.02	0.03
	1.2	33.89	51.20	0.03	31.13	44.58	0.08
	1.5	38.51	50.53	0.15	33.77	35.02	0.47
20X	0.2	5.43	84.60	0.06	2.99	105.37	1.94
	0.6	26.30	19.82	3.30	17.90	86.63	0.05
	0.9	34.68	21.34	1.18	26.44	53.15	0.27
	1.2	36.25	18.31	0.19	29.57	42.46	0.20
	1.5	39.20	21.83	0.49	34.34	40.36	0.11

Appendix C. Statistical analyses of NH₄-N (mg/kg) in biosolids-amended soil

C.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	2.27	32.59	0.02
	0.6	2.68	60.17	0.21
	0.9	3.80	86.18	0.72
	1.2	2.72	34.94	0.01
	1.5	3.00	52.20	0.00
5X	0.2	2.33	25.79	0.59
	0.6	2.67	57.62	0.27
	0.9	2.96	65.82	1.32
	1.2	2.54	35.15	1.27
	1.5	2.72	44.76	1.73
10X	0.2	1.80	22.06	45.93
	0.6	2.09	70.01	8.63
	0.9	2.53	73.44	6.73
	1.2	2.14	33.96	22.53
	1.5	2.31	46.90	14.09

C.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	1.94	25.94	16.24
	0.6	2.29	67.61	4.42
	0.9	2.61	71.64	5.48
	1.2	2.42	30.29	7.77
	1.5	2.38	46.49	10.61
5X	0.2	1.91	26.79	18.45
	0.6	3.05	83.73	0.45
	0.9	2.61	71.80	5.36
	1.2	2.50	30.78	4.62
	1.5	2.33	48.04	12.43
10X	0.2	1.75	26.63	48.31
	0.6	2.30	68.56	5.01
	0.9	2.00	12.75	11.84
	1.2	2.50	31.58	5.90
	1.5	2.32	37.45	0.64
20X	0.2	2.02	38.72	3.71
	0.6	2.35	68.36	3.90
	0.9	2.69	77.64	3.52
	1.2	2.48	34.30	4.50
	1.5	2.81	54.57	0.54

C.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	NA	NA	NA
	0.6	NA	NA	NA
	0.9	2.94	72.43	2.94
	1.2	1.94	36.91	41.30
	1.5	2.38	47.71	13.76
5X	0.2	2.18	21.23	3.92
	0.6	1.98	12.93	20.42
	0.9	1.84	13.42	55.65
	1.2	2.17	34.99	0.00
	1.5	2.22	27.85	0.00
10X	0.2	2.45	17.36	13.14
	0.6	2.15	11.88	3.92
	0.9	2.39	9.79	57.18
	1.2	2.30	25.29	2.87
	1.5	2.54	14.03	20.28
20X	0.2	2.56	28.90	8.25
	0.6	2.31	15.87	7.75
	0.9	2.41	16.69	14.93
	1.2	2.83	24.70	15.25
	1.5	2.87	15.94	42.32

Appendix D. Statistical analyses of NO₃-N (mg/kg) in biosolids-amended soil

D.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	9.00	132.97	1.58
	0.6	29.56	102.99	1.45
	0.9	54.50	80.58	2.65
	1.2	68.40	67.49	4.13
	1.5	93.59	52.14	6.06
5X	0.2	26.74	106.51	18.20
	0.6	38.92	67.54	12.47
	0.9	70.74	58.23	0.40
	1.2	87.99	48.22	0.31
	1.5	114.52	36.84	0.02
10X	0.2	33.27	85.97	31.56
	0.6	36.20	61.99	11.61
	0.9	73.10	61.24	0.80
	1.2	89.67	47.19	0.64
	1.5	119.87	43.56	0.52

D.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	6.75	129.90	0.03
	0.6	18.92	102.18	1.98
	0.9	50.83	82.30	4.99
	1.2	65.07	67.99	6.61
	1.5	86.76	51.41	13.05
5X	0.2	7.00	129.83	0.11
	0.6	28.90	98.10	1.33
	0.9	58.84	74.65	1.07
	1.2	74.79	56.54	1.72
	1.5	101.02	42.81	3.05
10X	0.2	18.97	138.87	8.08
	0.6	50.91	57.20	32.01
	0.9	77.14	62.46	1.78
	1.2	90.31	52.89	0.70
	1.5	121.24	38.14	1.11
20X	0.2	17.69	94.34	16.21
	0.6	60.87	59.74	38.11
	0.9	94.38	72.54	6.01
	1.2	113.61	60.50	6.67
	1.5	147.14	46.14	8.78

D.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	18.34	66.41	34.08
	0.6	36.28	63.14	11.29
	0.9	84.35	57.17	4.98
	1.2	103.16	44.23	6.33
	1.5	140.86	31.64	12.01
5X	0.2	11.89	97.05	7.88
	0.6	38.07	90.64	6.46
	0.9	66.25	70.47	0.00
	1.2	87.23	61.96	0.13
	1.5	134.21	47.65	3.73
10X	0.2	10.71	103.46	5.22
	0.6	37.58	97.05	5.40
	0.9	72.29	74.25	0.43
	1.2	80.10	61.48	0.23
	1.5	101.23	48.57	2.28
20X	0.2	9.74	101.08	3.92
	0.6	24.84	86.77	0.15
	0.9	66.34	83.83	0.00
	1.2	70.45	66.39	3.04
	1.5	95.45	47.08	5.88

Appendix E. Statistical analyses of total P (mg/kg) in biosolids-amended soil

E.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	741.84	14.02	0.12	706.36	19.49	0.07
	0.6	607.55	11.73	6.49	575.38	22.16	0.01
	0.9	613.13	13.57	0.24	590.60	17.53	0.01
	1.2	548.20	10.81	5.35	601.13	21.26	6.84
	1.5	610.23	4.96	17.63	613.96	16.68	1.58
5X	0.2	727.81	15.21	0.19	728.83	14.52	0.87
	0.6	656.30	20.80	0.66	603.47	15.44	3.90
	0.9	650.37	13.09	4.59	676.61	16.44	20.85
	1.2	579.03	13.22	17.69	619.48	16.90	18.00
	1.5	591.39	15.41	0.02	649.75	15.21	12.07
10X	0.2	876.56	18.05	28.51	779.88	11.20	21.48
	0.6	674.55	10.66	9.40	621.47	16.54	8.07
	0.9	663.22	13.41	8.51	673.47	12.85	31.91
	1.2	539.63	15.13	1.10	593.67	17.53	7.73
	1.5	609.46	8.04	6.26	593.70	13.66	0.01

E.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	699.81	20.45	2.27	715.83	15.75	0.03
	0.6	571.86	15.68	19.47	542.26	17.65	3.67
	0.9	593.31	20.70	1.70	620.75	15.22	3.34
	1.2	532.70	23.34	0.13	609.63	18.27	11.96
	1.5	597.32	6.55	1.61	641.00	10.83	17.57
5X	0.2	777.55	14.34	5.06	709.37	19.35	0.02
	0.6	650.21	11.10	1.06	586.51	19.34	0.53
	0.9	673.09	11.79	16.14	614.76	14.86	2.24
	1.2	604.53	11.70	45.11	644.51	15.30	36.35
	1.5	601.18	6.17	3.86	573.28	22.64	0.79
10X	0.2	720.63	24.95	0.25	753.10	15.28	4.50
	0.6	619.11	12.41	2.13	605.99	16.26	4.08
	0.9	615.31	12.78	0.13	656.65	20.16	8.59
	1.2	570.10	10.18	21.40	610.05	16.86	16.11
	1.5	587.19	5.50	0.12	601.84	13.39	0.55
20X	0.2	785.06	16.14	5.46	775.83	11.45	18.36
	0.6	627.78	13.35	0.52	1035.81	154.46	3.01
	0.9	591.98	18.34	2.39	686.45	13.33	38.39
	1.2	503.35	19.53	1.80	633.01	20.34	16.65
	1.5	544.03	11.96	17.23	617.96	13.58	3.31

E.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	720.83	14.32	0.75	700.67	20.16	0.25
	0.6	623.78	11.26	1.44	572.66	15.98	0.00
	0.9	620.92	12.60	0.01	608.20	12.95	1.53
	1.2	558.82	10.29	12.20	578.63	17.41	3.91
	1.5	597.77	5.25	2.79	605.04	14.29	0.76
5X	0.2	750.68	13.83	0.74	765.03	13.36	9.54
	0.6	640.04	11.40	0.03	622.51	14.65	10.69
	0.9	625.20	12.42	0.16	608.09	12.90	1.52
	1.2	557.47	10.38	11.08	605.96	16.62	13.00
	1.5	605.99	5.99	7.85	597.24	15.52	0.09
10X	0.2	753.37	13.94	1.01	765.84	10.95	14.61
	0.6	637.03	11.17	0.00	601.08	16.37	2.97
	0.9	591.11	14.54	4.06	577.81	15.30	0.92
	1.2	1040.31	151.30	3.85	545.86	18.38	0.00
	1.5	590.48	4.75	0.09	593.21	8.87	0.01
20X	0.2	731.36	13.81	0.07	801.97	21.19	9.99
	0.6	614.55	11.89	3.65	577.92	19.24	0.08
	0.9	590.49	13.48	4.94	574.22	14.84	1.56
	1.2	526.93	10.96	0.03	570.58	17.81	2.21
	1.5	581.02	4.86	2.90	656.24	25.12	5.38

Appendix F. Statistical analyses of Olsen P (mg/kg) in biosolids-amended soil

F.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	8.48	79.33	6.18
	0.6	3.81	76.52	0.61
	0.9	3.86	118.49	0.74
	1.2	4.74	77.30	0.93
	1.5	5.12	40.88	1.67
5X	0.2	6.65	34.67	10.43
	0.6	3.69	78.82	1.19
	0.9	4.43	104.26	0.01
	1.2	4.78	75.80	0.85
	1.5	5.67	39.24	0.07
10X	0.2	12.82	57.64	37.96
	0.6	3.44	83.32	2.85
	0.9	3.68	123.50	1.21
	1.2	5.16	73.91	0.07
	1.5	5.54	40.12	0.01

F.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	6.31	43.42	1.84
	0.6	3.47	81.33	2.38
	0.9	3.60	125.97	1.47
	1.2	4.66	77.93	1.23
	1.5	5.21	40.64	1.05
5X	0.2	6.04	35.42	1.09
	0.6	3.74	77.39	0.86
	0.9	3.72	121.85	1.10
	1.2	4.58	78.45	1.57
	1.5	5.53	37.69	0.01
10X	0.2	7.63	59.44	8.78
	0.6	3.78	81.16	0.66
	0.9	3.93	117.68	0.57
	1.2	4.49	83.16	2.09
	1.5	5.39	42.55	0.29
20X	0.2	7.69	37.70	22.76
	0.6	3.62	77.66	1.48
	0.9	3.74	121.29	1.04
	1.2	4.92	74.23	0.47
	1.5	5.69	36.74	0.12

F.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	7.44	47.39	9.99
	0.6	3.77	74.75	0.80
	0.9	3.96	116.01	0.53
	1.2	5.04	72.86	0.22
	1.5	5.24	41.13	0.80
5X	0.2	8.00	69.93	6.95
	0.6	5.58	96.84	2.38
	0.9	4.98	104.19	0.38
	1.2	5.01	79.48	0.39
	1.5	6.62	42.09	5.81
10X	0.2	6.78	39.32	6.03
	0.6	4.13	71.60	0.01
	0.9	4.38	106.85	0.03
	1.2	5.21	72.06	0.04
	1.5	6.23	36.91	2.98
20X	0.2	8.61	72.36	7.88
	0.6	3.75	74.36	0.90
	0.9	4.38	107.22	0.03
	1.2	5.02	72.99	0.26
	1.5	5.68	38.53	0.10

Appendix G. Statistical analyses of As (mg/kg) in biosolids-amended soil

G.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	4.62	12.89	0.52
	0.6	5.71	17.68	2.63
	0.9	8.10	27.20	0.74
	1.2	7.74	17.35	0.09
	1.5	10.29	9.45	90.54
5X	0.2	4.54	12.84	1.13
	0.6	6.48	15.17	0.06
	0.9	8.76	19.71	0.03
	1.2	7.07	17.00	1.04
	1.5	10.20	11.01	71.57
10X	0.2	4.68	13.14	0.21
	0.6	6.20	19.26	0.14
	0.9	9.24	19.10	0.25
	1.2	7.85	17.77	0.23
	1.5	11.16	12.74	25.11

G.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	10.78	151.81	0.80
	0.6	5.33	17.08	8.07
	0.9	7.71	22.44	2.71
	1.2	7.15	15.86	0.84
	1.5	10.64	11.23	49.63
5X	0.2	4.45	13.94	1.82
	0.6	5.80	16.04	2.36
	0.9	8.31	21.77	0.59
	1.2	7.89	14.78	0.43
	1.5	10.65	9.63	66.99
10X	0.2	4.37	16.72	2.01
	0.6	5.80	16.12	2.30
	0.9	7.60	22.90	3.23
	1.2	8.10	15.95	1.00
	1.5	10.20	8.88	109.57
20X	0.2	4.82	22.95	0.00
	0.6	5.81	15.58	2.41
	0.9	8.55	27.14	0.12
	1.2	7.85	19.15	0.20
	1.5	10.87	9.57	56.94

G.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	3.78	8.36	0.02
	0.6	4.45	16.91	2.70
	0.9	7.11	16.72	3.69
	1.2	6.87	17.10	0.09
	1.5	25.56	162.98	1.13
5X	0.2	4.27	27.64	1.11
	0.6	10.02	125.86	0.97
	0.9	7.26	14.73	3.16
	1.2	7.37	11.82	3.24
	1.5	26.51	157.28	1.02
10X	0.2	4.11	11.81	3.09
	0.6	5.64	13.01	5.18
	0.9	8.16	14.16	0.07
	1.2	7.93	18.84	3.89
	1.5	27.70	150.59	0.88
20X	0.2	4.38	7.21	22.85
	0.6	6.17	23.16	4.32
	0.9	9.30	28.83	1.33
	1.2	9.47	28.01	6.41
	1.5	27.90	149.36	0.86

Appendix H. Statistical analyses of Cu (mg/kg) in biosolids-amended soil

H.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	1.91	59.94	1.06	13.46	162.20	1.40
	0.6	2.97	84.73	0.07	12.70	195.18	2.20
	0.9	3.36	136.67	1.12	7.80	67.48	0.26
	1.2	2.41	137.33	0.63	11.07	143.76	1.86
	1.5	1.43	180.98	0.17	13.92	164.14	2.88
5X	0.2	1.22	58.79	16.06	7.18	39.32	17.61
	0.6	1.70	67.53	4.60	5.70	53.90	2.92
	0.9	0.72	235.88	0.92	6.50	55.77	1.99
	1.2	1.78	161.62	2.10	5.91	42.13	13.75
	1.5	0.96	236.90	0.93	5.79	60.34	8.22
10X	0.2	2.36	85.46	0.00	NA	NA	NA
	0.6	4.87	112.28	0.95	4.53	43.40	39.07
	0.9	1.29	156.72	0.01	5.12	47.88	29.92
	1.2	3.68	150.89	0.01	5.18	37.70	48.43
	1.5	3.08	186.25	0.27	6.02	64.75	4.88

H.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	3.32	53.60	1.61	NA	NA	NA
	0.6	1.94	61.67	2.39	NA	NA	NA
	0.9	3.15	73.36	3.51	NA	NA	NA
	1.2	4.12	77.31	0.24	NA	NA	NA
	1.5	3.19	82.83	1.88	NA	NA	NA
5X	0.2	4.14	89.77	1.32	NA	NA	NA
	0.6	2.80	107.62	0.01	NA	NA	NA
	0.9	4.29	49.86	11.10	5.34	54.26	17.49
	1.2	6.32	58.36	3.57	5.37	44.84	26.79
	1.5	1.27	191.03	0.36	NA	NA	NA
10X	0.2	5.67	100.26	1.99	9.35	111.03	0.01
	0.6	7.94	14.11	131.18	16.57	291.78	1.54
	0.9	7.72	27.48	53.60	5.90	61.29	5.80
	1.2	10.46	27.77	34.68	5.75	46.43	14.72
	1.5	5.54	44.09	13.59	NA	NA	NA
20X	0.2	12.98	21.10	89.65	NA	NA	NA
	0.6	8.34	36.31	20.81	NA	NA	NA
	0.9	6.09	57.88	10.71	NA	NA	NA
	1.2	6.40	51.91	5.80	5.93	54.50	7.92
	1.5	4.90	112.66	1.82	5.81	60.08	7.94

H.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	9.80	17.26	1.03	NA	NA	NA
	0.6	9.04	6.55	82.67	5.17	53.79	9.24
	0.9	8.00	36.82	0.00	8.37	151.30	0.23
	1.2	8.72	13.96	4.28	10.07	150.24	1.08
	1.5	8.71	16.46	5.86	6.09	64.53	4.37
5X	0.2	10.60	9.57	0.06	9.49	29.05	0.52
	0.6	10.75	3.13	12.37	6.09	52.83	0.82
	0.9	9.00	31.05	0.81	7.42	47.05	0.01
	1.2	8.99	11.24	10.01	8.36	47.13	1.92
	1.5	9.29	22.83	0.93	7.24	55.82	0.10
10X	0.2	11.38	15.46	1.51	6.43	35.80	50.69
	0.6	9.25	48.42	1.18	5.67	55.14	3.00
	0.9	6.73	63.39	0.50	6.25	55.23	3.67
	1.2	7.45	31.58	0.06	5.25	39.87	39.77
	1.5	10.51	14.36	0.39	5.81	60.04	8.02
20X	0.2	10.54	10.46	0.01	NA	NA	NA
	0.6	10.26	5.21	19.79	NA	NA	NA
	0.9	8.51	34.48	0.21	NA	NA	NA
	1.2	8.48	10.72	4.55	NA	NA	NA
	1.5	10.72	13.07	1.06	NA	NA	NA

Appendix I. Statistical analyses of Ni (mg/kg) in biosolids-amended soil

I.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	116.46	14.25	0.03	33.78	131.33	0.16
	0.6	124.67	11.72	0.30	23.78	62.01	2.62
	0.9	116.55	11.96	0.07	21.97	31.57	10.20
	1.2	118.70	10.69	6.93	28.81	115.02	0.39
	1.5	111.24	18.21	0.00	31.63	119.29	0.55
5X	0.2	98.50	8.19	33.66	21.01	72.94	14.64
	0.6	111.95	18.60	3.54	18.96	76.68	13.18
	0.9	115.63	8.87	0.35	17.46	32.21	76.45
	1.2	112.52	10.29	17.59	17.37	28.03	96.43
	1.5	104.98	12.94	1.20	18.82	31.21	69.31
10X	0.2	100.68	12.32	11.17	24.26	74.34	4.71
	0.6	111.32	16.99	4.63	20.62	81.61	6.49
	0.9	105.17	13.02	5.35	20.01	65.53	6.68
	1.2	105.83	13.79	19.81	19.30	56.17	11.18
	1.5	96.08	18.61	4.22	24.18	55.12	1.58

I.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	93.76	7.12	95.67	26.58	74.98	1.60
	0.6	97.93	13.09	41.07	22.21	72.27	4.30
	0.9	113.53	26.80	0.14	21.02	43.44	9.28
	1.2	121.03	25.88	0.78	20.48	51.92	7.51
	1.5	88.52	13.08	22.75	25.56	59.13	0.31
5X	0.2	114.70	6.72	0.85	22.62	71.39	9.21
	0.6	112.95	13.67	5.65	19.48	76.81	11.03
	0.9	116.80	6.79	0.16	18.69	45.34	24.35
	1.2	126.27	7.41	2.52	17.94	34.56	51.21
	1.5	89.35	13.58	19.23	NA	NA	NA
10X	0.2	97.21	17.55	8.57	24.61	69.12	4.74
	0.6	100.84	11.84	30.91	25.64	77.07	0.41
	0.9	96.85	8.31	41.85	21.69	48.84	5.04
	1.2	122.44	31.63	0.39	31.61	81.79	2.40
	1.5	84.09	11.57	46.18	20.83	41.23	20.84
20X	0.2	97.14	15.80	10.67	25.42	80.17	2.50
	0.6	108.22	17.94	6.19	23.25	72.69	2.56
	0.9	118.22	29.44	0.00	20.66	52.26	7.73
	1.2	113.80	18.60	4.60	18.23	38.82	36.30
	1.5	104.05	22.13	0.56	NA	NA	NA

I.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	26.23	9.20	4.12	39.64	191.16	0.49
	0.6	24.32	4.00	98.72	20.52	81.03	6.82
	0.9	23.93	13.89	0.27	25.21	73.74	0.02
	1.2	25.38	5.43	0.11	20.05	68.37	5.37
	1.5	16.83	11.43	68.62	22.07	41.07	10.52
5X	0.2	26.90	3.00	16.33	NA	NA	NA
	0.6	27.08	3.42	9.81	NA	NA	NA
	0.9	25.17	11.05	0.22	NA	NA	NA
	1.2	25.82	3.99	0.35	NA	NA	NA
	1.5	17.46	12.66	62.48	NA	NA	NA
10X	0.2	26.78	2.83	22.00	NA	NA	NA
	0.6	25.08	7.56	16.91	NA	NA	NA
	0.9	22.85	14.09	1.84	NA	NA	NA
	1.2	24.87	9.80	0.50	NA	NA	NA
	1.5	18.33	6.37	281.99	NA	NA	NA
20X	0.2	60.15	135.55	0.92	NA	NA	NA
	0.6	25.90	3.40	43.46	NA	NA	NA
	0.9	23.90	12.38	0.37	NA	NA	NA
	1.2	25.27	6.37	0.21	NA	NA	NA
	1.5	18.31	9.17	135.66	NA	NA	NA

Appendix J. Statistical analyses of Se (mg/kg) in biosolids-amended soil

J.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	NA	NA	NA
	0.6	NA	NA	NA
	0.9	0.22	113.69	2.80
	1.2	0.13	122.05	3.82
	1.5	0.27	84.73	8.15
5X	0.2	0.24	117.07	0.34
	0.6	5.25	234.33	1.06
	0.9	0.32	112.68	0.32
	1.2	0.19	114.87	0.58
	1.5	0.36	87.43	2.02
10X	0.2	0.51	56.32	2.91
	0.6	5.50	223.91	0.96
	0.9	0.46	61.30	0.33
	1.2	0.34	46.25	1.88
	1.5	0.62	50.39	0.46

J.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	0.22	112.72	0.79
	0.6	5.25	234.71	1.06
	0.9	0.28	110.66	0.92
	1.2	0.25	131.59	0.00
	1.5	0.33	83.61	3.19
5X	0.2	0.43	48.69	2.01
	0.6	5.42	227.15	0.99
	0.9	0.54	48.18	1.79
	1.2	0.38	44.16	3.30
	1.5	0.55	45.07	0.01
10X	0.2	0.44	45.06	2.58
	0.6	5.51	223.55	0.96
	0.9	0.50	52.13	0.90
	1.2	0.44	35.69	8.65
	1.5	0.55	42.56	0.03
20X	0.2	0.34	91.73	0.06
	0.6	5.49	224.16	0.97
	0.9	0.42	87.54	0.02
	1.2	0.29	91.98	0.12
	1.5	0.46	74.33	0.35

J.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Mean value	Coefficient variable	F value
1X	0.2	0.33	49.74	1.53
	0.6	0.40	24.31	0.02
	0.9	0.32	38.69	0.58
	1.2	0.28	26.92	0.29
	1.5	0.41	24.36	24.25
5X	0.2	0.26	47.06	0.13
	0.6	0.44	29.98	0.60
	0.9	0.34	21.63	4.36
	1.2	0.22	26.98	3.82
	1.5	0.55	22.85	0.94
10X	0.2	0.30	60.91	0.60
	0.6	0.44	27.32	0.67
	0.9	0.30	45.18	0.09
	1.2	0.31	35.23	1.23
	1.5	0.63	15.25	0.46
20X	0.2	0.37	36.00	5.33
	0.6	0.46	21.00	2.24
	0.9	0.42	28.77	7.80
	1.2	0.43	33.35	8.30
	1.5	0.67	27.97	0.69

Appendix K. Statistical analyses of Zn (mg/kg) in biosolids-amended soil

K.1. Lime-stabilized biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	40.04	9.69	2.71	83.56	114.57	4.03
	0.6	115.12	177.58	0.87	52.80	17.11	42.67
	0.9	34.00	14.78	3.53	54.50	23.48	18.71
	1.2	32.09	13.18	0.04	50.49	19.24	36.82
	1.5	36.76	7.77	0.59	76.18	109.81	4.49
5X	0.2	40.40	12.91	1.12	53.07	18.88	0.86
	0.6	36.93	19.37	0.02	45.11	25.71	1.22
	0.9	39.44	12.37	0.63	48.38	20.21	3.64
	1.2	37.37	8.94	17.12	44.62	17.90	6.36
	1.5	34.81	30.94	0.06	45.68	23.39	0.29
10X	0.2	50.13	10.07	13.17	49.11	13.87	4.54
	0.6	37.80	6.96	0.17	42.13	17.73	0.45
	0.9	40.63	15.68	1.13	45.88	13.78	0.33
	1.2	30.49	9.58	1.08	38.58	15.50	7.21
	1.5	34.72	12.75	0.40	42.78	24.50	4.90

K.2. Aerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	44.53	9.55	1.47	46.48	13.74	22.46
	0.6	34.70	2.85	53.98	37.03	20.79	21.37
	0.9	38.55	13.05	0.14	40.88	16.73	14.84
	1.2	35.30	8.93	9.62	40.68	15.60	0.30
	1.5	39.38	7.38	8.77	44.09	10.56	10.84
5X	0.2	48.09	15.32	3.28	51.81	15.10	0.05
	0.6	39.80	6.31	5.67	43.21	20.70	0.03
	0.9	41.07	12.07	2.52	45.76	14.43	0.20
	1.2	40.64	14.15	14.39	44.68	13.17	12.17
	1.5	36.76	14.32	0.17	42.79	20.22	7.15
10X	0.2	44.73	21.66	0.28	50.37	14.60	0.89
	0.6	37.29	2.92	0.02	42.34	16.22	0.30
	0.9	38.15	12.59	0.02	44.47	13.95	0.61
	1.2	39.40	6.80	49.13	42.00	14.36	0.62
	1.5	34.77	10.38	0.55	42.38	11.86	29.40
20X	0.2	54.42	23.85	4.94	50.25	12.78	1.42
	0.6	40.52	15.51	1.52	41.45	18.00	1.49
	0.9	40.09	17.59	0.75	46.21	13.28	0.83
	1.2	39.26	35.61	1.74	44.27	22.33	3.34
	1.5	40.43	29.35	0.89	42.25	11.30	30.56

K.3. Anaerobically digested biosolids-amended soil

Multiple of agronomic rate	Depth (m)	Year 1			Year 2		
		Mean value	Coefficient variable	F value	Mean value	Coefficient variable	F value
1X	0.2	48.52	11.15	1.95	50.14	15.21	1.18
	0.6	41.90	3.61	90.44	40.78	18.27	3.11
	0.9	44.43	11.93	0.62	45.41	14.91	0.02
	1.2	44.10	10.24	6.59	43.23	15.34	3.61
	1.5	46.95	14.16	0.01	47.13	10.82	0.32
5X	0.2	51.50	6.53	0.01	52.41	15.82	0.41
	0.6	47.47	4.12	0.14	42.59	16.62	0.12
	0.9	45.72	6.81	0.11	45.04	13.82	0.05
	1.2	43.67	5.73	17.74	42.12	13.32	0.85
	1.5	46.37	3.11	1.85	44.58	12.60	4.87
10X	0.2	52.88	3.07	3.75	90.31	176.48	2.13
	0.6	46.57	4.39	2.07	42.88	17.31	0.00
	0.9	42.83	6.36	8.81	41.03	15.69	15.67
	1.2	43.32	5.27	17.99	38.31	14.16	10.67
	1.5	48.03	1.67	6.97	44.53	7.70	13.79
20X	0.2	51.60	2.45	0.00	49.39	28.27	0.84
	0.6	45.53	3.54	11.50	31.73	45.27	22.04
	0.9	42.58	7.64	7.14	NA	NA	NA
	1.2	41.58	8.53	2.34	NA	NA	NA
	1.5	46.95	4.23	0.07	NA	NA	NA

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- Graduate Grade Point Average 3.7/4.0 index (Doctor of Philosophy)
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- 2001 Viet Nam Department of Education Scientific Research Award
- 2001 Ho Chi Minh City Department of Science, Technology, and Environment Research Award

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Graduate research assistant – Utah State University, Logan
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- Studied effects of biosolids land application on nutrient mobility in disturbed rangeland
- Simulated nitrate leaching at biosolids land application sites

Graduate research assistant – University of Utah, Salt Lake City
05/2002-03/2005

- Modeled silica vaporization during coal combustion
- Conducted validation experiments for silica and arsenic vaporization using a high temperature drop tube furnace
- Trained and supervised an undergraduate research assistant

Teaching Assistant – HCMC University of Technology, Ho Chi Minh City, Vietnam

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- Helped students solve problems in Air Pollution Control
- Graded assignments and tests
- Presented supplementary class lectures

Student Engineer – HCMC Department of Science, Ho Chi Minh City, Vietnam
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- Waste water treatment of a tannery
- Emphasized chromium removal

Conference Interpreter – Polymer Conference, Ho Chi Minh City, Vietnam

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Publications and Conference Papers:

- M. Vutran, M. J. McFarland, I. Vasquez, M. Schmitz and R. B. Brobst (2008) “**Phosphorus Mobility on Biosolids-Amended Rangelands**”. Submitted to Journal of Environmental Quality.
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- Vutran, M., Lighty, J.S., Sarofim, A.F., Robertson, J.D., and Haynes, B.S. (2003) **“The Role of CO₂ in the Vaporization of Metal Oxides from Coal Combustion”**. Congress on Combustion Byproducts, 06/2003, Umea, Sweden.

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