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PHOSPHORUS BIOAVAILABILITY AND CONTROL OF RUNOFF LOSSES IN LAND APPLIED BIOSOLIDS

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Phosphorus Bioavailability and Control of Runoff Losses in Land Applied Biosolids

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF PHOTOGRAPHS

LIST OF ACRONYMS

Abbreviation/Acronym	Definition
AD	air-dried
Al	aluminum
Ca	calcium
CC	centrifuge cake
CSC	Soil Conservation Services
CU	Coefficient of Uniformity
DPS	degree of phosphorus saturation
DMRP	dissolved molybdate reactive phosphorus
DRP	dissolved reactive phosphate
DM	dry matter
EQ	Exceptional Quality
FC	field capacity
Fe	iron
IEPA	Illinois Environmental Protection Agency
K	potassium
Mg	magnesium
Mn	mangnese
N	nitrogen
NH_3-N	ammonia nitrogen
NH_4NO_3	ammonium nitrate
NO_3-N	nitrate nitrogen
NPRP	National Phosphorus Research Project
OX	oxalate extractable
P	phoshorus
PSI	Phosphorus Saturation Index
PWSP	water soluble P as a percent of Total P
RO	reverse osmosis
TKN	total Kjeldahl nitrogen
TP	total phosphorus
TSP	triple superphosphate
USEPA	United States Environmental Protection Agency
WRP	water reclamation plant
WSP	water soluble phosphorus

EXECUTIVE SUMMARY

Background

Biosolids and other organic amendments are typically applied to cropland based on the agronomic nitrogen (N) requirement. Due to greater phosphorus (P) loading beyond crop needs associated with N-based applications, there are concerns that the excess P can be lost from agricultural land through surface runoff and cause the contamination of water bodies. Most of the P runoff losses from agricultural fields are in the form of particulate P through soil erosion, and up to 20 percent is in the soluble form (Sharpley et al., 2003). These concerns have prompted federal efforts in conducting research and developing guidelines to minimize the contamination of water bodies resulting from P losses from agricultural land. Also, many states are adopting regulations and guidelines to address the issue. The Water Quality Improvement Act of Maryland mandates P-based nutrient management for manures and biosolids; similarly, in Florida, P-based biosolids application is required in sensitive watersheds (Elliott et al., 2006).

According to the United States Environmental Protection Agency (USEPA) design manual, phosphorus-based biosolids recommendations are developed on the basis that the relative effectiveness of biosolids P compared with fertilizer P is only 50 percent (USEPA, 1995). Many other literature reports range from 10 percent to 100 percent effectiveness from greenhouse studies. In Canada, a value of 40 percent effectiveness is recommended (Ontario Ministry of Agriculture, Food, and Rural Affairs, 1996). The relative effectiveness factor tacitly acknowledges that a large fraction of P in biosolids may be strongly bound with other biosolids constituents and is not readily available to plants or is present in forms which may not be lost readily as soluble P in leaching or runoff. The unavailable fraction of P is bound mainly with metals, like iron (Fe), aluminum (Al), calcium (Ca), and magnesium (Mg), or may be present in organic form that may need to be mineralized to become available to plants. Previous studies indicate that Ca-bound P is more readily available than Al- and Fe-bound P. Therefore, biosolids chemically treated with Ca will generally have higher available P as compared to biosolids treated with Fe and Al. The molar ratio of P to (Al + Fe) is often used as an indicator of P-binding potential and hence, P-supplying power of biosolids. In this concept, a ratio > 1 indicates that P-binding sites are saturated, and biosolids are capable of supplying large amounts of soluble P, whereas a ratio of < 1 may indicate low P saturation and subsequently lower bioavailability and potential for losses of soluble P in leaching or runoff water.

The bioavailability of biosolids P is further influenced by soil characteristics when they are land applied and mixed with soil. Based on soil properties, the soluble biosolids P forms interact with soil constituents and become bound in reaction products with varying solubilities and bioavailabilities. Further, the added biosolids alter soil properties such as pH, P adsorption capacity, Fe and Al content, soluble salts, organic acids, and other competing ions that can alter P solubility. A collaborative study between the University of Saskatchewan, Canada, and the Metropolitan Water Reclamation District of Greater Chicago (District), using soils which received long-term applications of biosolids at the District's Fulton County site, showed that P extraction from soil depended strongly on the fertilizer source (Kar et al., 2011). The study also showed that P in biosolids-amended soil was predominantly in a dicalcium phosphate solid fraction and Fe- and Al-phosphate forms, while P in triple superphosphate (TSP)-fertilized soils was present as adsorbed and calcium-phosphate forms. These differences in the forms of P resulted in higher labile P in the TSP-fertilized soil than in biosolids-amended soils, although the total P (TP) was higher in the biosolids-amended soils.

Objectives

In collaboration with the Illinois Environmental Protection Agency (IEPA), the District developed a set of studies to generate information that will be useful to the IEPA for developing biosolids land-application guidelines to minimize P losses from agricultural fields in Illinois. The studies were conducted with the overall objectives to determine the following:

1. Relative bioavailability of biosolids P.
2. Residual bioavailability of biosolids P.
3. Potential for surface runoff of biosolids P, and the effect of incorporation on reducing P runoff losses.
4. Width of buffer zone required to limit P runoff losses.
5. Whether a phosphorus index system is more appropriate than cumulative loading rates for setting biosolids loading limits.

Results

Bioavailability of Biosolids Phosphorus. Greenhouse and field studies were conducted to address Objectives 1 and 2. The greenhouse study (Chapter 1) was conducted to determine the bioavailability of P in Class B centrifuge cake (CC) biosolids and lagoon-aged, air-dried biosolids (AD) relative to inorganic fertilizer TSP. The biosolids and TSP as P sources were applied at seven targeted P rates (0 to 300 mg P kg^{-1}) to a P-deficient Immokalee fine sand. A 15-cm layer of the amended soil was placed on top of a 23-cm unamended soil layer in pots in the greenhouse and cropped for 18 consecutive 35-day cropping cycles of alternating crops of wheat (*Triticum aestivum* L.) and perennial ryegrass (*Lolium perene* L.). The results from this study showed that the extractability of applied biosolids P was lower than chemical fertilizer P, and biosolids were less effective in increasing Bray-1 soil test P. The bioavailability of CC biosolids and AD biosolids was 28 percent and 42 percent in the short term (three cropping cycles) and almost doubled to 61 percent and 85 percent in the long run (18 cropping cycles), respectively, in comparison to inorganic fertilizer TSP. These results show that the agronomic P rates for these biosolids should be greater than the agronomic rates for chemical fertilizers. Bioavailability of biosolids P is lower than that of chemical fertilizer P in the short term, and it increases slowly over time, which makes it less prone to soluble P losses.

The field study (Chapter 2) was conducted from 2005 to 2008 at the District's Fulton County site, Western Illinois, with lagoon-aged, AD biosolids applied at a series of P rates (0, 75, 150, 225, 300 mg P kg^{-1} soil) along with commercial P fertilizer - TSP as a reference. The highest P rate was equivalent to the amount of P that may be applied based on an N-based biosolids application rate of 22.4 Mg ha^{-1} for row crops in Illinois. Biosolids and TSP were incorporated into the surface soil once at the end of 2005, and corn (*Zea mays)* was planted for three consecutive years (2006 to 2008). The results showed that the increases in soil Bray-1 and water-soluble P (WSP) concentrations in response to P application were always lower in biosolids than in TSP treatments. However, the increases in Mehlich-3 extractable P were similar. The decline in extractable P over time, primarily due to crop uptake, varied among the P rates but was lower for biosolids P than for TSP. There were no significant differences in crop P uptake among the treatments, but the P concentrations in corn tissues were lower in biosolids than in TSP treatments. These results corroborate the findings from the greenhouse study, since they show that biosolids P is less effective than chemical fertilizer P in increasing soil extractable P; therefore, the agronomic rate of biosolids P should be greater than for chemical fertilizer P.

Potential for Surface Runoff of Biosolids Phosphorus. Three separate experiments were conducted to address Objective 3: two focused on laboratory analyses and simulated P runoff on soils amended with various rates of biosolids over time (Chapter 3), and the other using simulated P runoff on soils recently amended with biosolids (Chapter 4). In the first experiment, a total of 45 soil samples from 13 fields (sampled at various times) at the District's Fulton County site that received cumulative biosolids application rates from no application to as high as 1,073 Mg ha^{-1} during 33 years of reclamation (Chapter 3) were analyzed along with the data used to evaluate the potential for runoff P losses from these fields. The specific objectives of this study were to estimate the potential for P losses in biosolids-amended soil and the biosolids P loading required to increase soil test P to the critical environmental impact threshold above which the potential for runoff P losses from agricultural fields increases significantly. Results showed that extractable P (Bray-1, Mehlich-3 P, and Oxalate-P, and WSP) increased with cumulative biosolids applications. The changes in extractable P (Bray-1, Mehlich-3 P or WSP) were highly correlated with the cumulative biosolids application. However, the increases in soil test P were not linear. Soil test P increased exponentially with cumulative biosolids applications, approaching a maximum at higher cumulative biosolids applications. This study is unique in that the cumulative biosolids application rates were very high. At such high P rates, soil extractable P levels approached a maximum in response to cumulative biosolids as expected because at such high application rates, biosolids represent a significant proportion of the 15-cm soil surface. This results in high P saturation, which is demonstrated by the relatively high extractable P and P saturation index (PSI) values.

The PSI and WSP data from the long-term biosolids application fields was well described by a Piecewise-2-Segment linear model, which showed the critical change point at a PSI of 31 and 10 mg kg^{-1} WSP. Above this critical point, WSP increases sharply with increasing PSI.

In the second experiment of this study (Chapter 3), the relationship between runoff P, WSP, and PSI from a simulated runoff study done on soils collected from 11 of the 13 fields was evaluated by regression analysis. The rainfall simulations used the National Phosphorus Research Project (NPRP) approach. The results showed that PSI was well correlated with WSP ($r^2 = 0.93$) runoff dissolved molybdate reactive P-DMRP ($r^2 = 0.94$). The critical change point above which there was a sharp increase in WSP or runoff DMRP losses was a PSI of 37 and 40, respectively, which were similar to those estimated from the first experiment (PSI 31) relating PSI with WSP. Thus, for long-term biosolids application fields, the critical P saturation was between 30 to 40 percent based on oxalate extractable P, Al, and Fe. Above this saturation point, there may be a greater risk of soluble P losses, either via leaching to groundwater or via runoff to surface waters. In literature, the soil P saturation values above 25 to 40 percent are often associated with greater risks of P loss in leaching and runoff and thus non-point source pollution.

The critical change point PSI value of 31 from the laboratory experiment and 37 and 40 from the runoff simulation experiment corresponded to cumulative biosolids application of 130 – 160 Mg ha^{-1}. Thus, the results from this study show that repeated and long-term application of the District's typical biosolids (containing ~ 2 percent TP) up to a cumulative loading of 160 Mg ha^{-1} may pose minimal risk of runoff P losses from the fields if agronomic best management practices are followed. Soils exceeding these biosolids loading rates or having P saturation greater than 40 percent may require greater management practices to minimize P loss from the fields.

In the third experiment, the potential of P losses in runoff from freshly applied biosolids (Chapter 4) was studied. The rainfall simulations were done using the NPRP approach. This study compared P losses in runoff generated by simulated rainfall from soil receiving TSP fertilizer applied at the recommended agronomic rate with two types of biosolids (Class B CC and Class A lagoon-aged and AD) either surface-applied or incorporated at rates equivalent to crop N (N-based) or P (P-based) requirements. Runoff samples were analyzed for DMRP, particulate P, and TP. The P source significantly affected DMRP concentration in runoff: TSP > AD biosolids > CC biosolids; DMRP concentrations ranged from 0.04 to 0.82 mg L^{-1}. Significantly greater TP concentrations (ranging from 5.7 to 13.0 mg L^{-1} for three runoff events) were observed when CC biosolids were surface-applied at an N-based rate than AD and TSP. Particulate P accounted for the major P losses, and both particulate P and TP losses were also significantly greater from CC biosolids than from AD biosolids or TSP. The N-based biosolids rate (surface-applied) produced greater runoff P losses than the P-based application rate; DMRP losses in runoff were reduced by 80 percent, and particulate P and TP losses were reduced by 33 percent when biosolids were applied at a P-based rate compared to an N-based rate. Incorporation of biosolids applied at N-based rates reduced DMRP losses by 50 percent and particulate P and TP losses by approximately 33 percent compared to surface application, and this reduced runoff P losses to the levels similar to losses from TSP fertilizer treatment. These results show that surface application of biosolids, which is not a typical application method, can make biosolids P more prone to runoff losses. However, incorporation of N-based rates of biosolids results in lower potential for P runoff losses, comparable to surface-applied, P-based biosolids rates or agronomic rates of chemical fertilizer P. Site management guidelines as specified in the USEPA's Part 503 regulations, such as incorporation of biosolids following application, are protective of surface water quality due to P losses in runoff from biosolids-applied land.

Width of Buffer Zone to Limit Phosphorus Runoff Losses. Runoff studies showed that most of the P from biosolids is lost in the form of particulate P, and controlling the transport of soil and biosolids particles may reduce the overall P losses. One of the best management practices often employed to reduce nutrient runoff is installing vegetative buffer strips. A field study (Chapter 5) was conducted at the District's Fulton County site to evaluate the effectiveness of 7.6 m (25 ft.) and 15.2 m (50 ft.) wide vegetative buffer zones (consisting of an alfalfa and bromegrass mixture) in controlling P runoff generated through natural precipitation. Results showed that sediment discharge at the edge of the buffers were lower than at the edge of the field, indicating that vegetative buffer strips were very effective in reducing the transport of particulate matter. On average over two years, a sediment reduction of 76 percent was observed when the buffer width was 7.6 m, and doubling the width only increased sediment reduction to 85 percent. Other studies have also shown that most of the sediments in runoff (53 – 86 percent of the input load) are retained in the first 5 m, but the optimum width can be as narrow as 1 – 2 m to significantly reduce sediment and nutrient losses.

Over both years, the average concentration of DMRP was not reduced by increasing the buffer width. However, a buffer width of 7.6 m was enough to reduce the runoff TP concentration in the year 2008 and 15.2 m for the year 2009. Averaged over the two years, a 7.6 m buffer was sufficient to reduce the TP concentration from biosolids treatments to below 1 mg L^{-1}.

In terms of P load, the width of buffer strips only marginally reduced DMRP losses from both TSP and biosolids treatments. However, a significant reduction in total P occurred for both years, and the effects were significant during rainfall runoff events compared to snowmelt runoff events. As observed for TP concentration, most of the reduction occurred within the buffer width of 7.6 m, and the reduction from a 7.6 m to a 15.2 m buffer width was relatively lower. The sediment rate is correlated with particulate P. A reduction in sediments results in a reduction in total P leaving the fields. Many previous studies have suggested a buffer width of 10 m, while others have demonstrated an acceptable effect (50 – 80 percent) with 3 – 5 m wide buffers. Relative mass loss of phosphorus in runoff was related to the width of buffer strips, according to first order equation. The present study also showed that a majority of losses in total P could be controlled by a 7.6 m wide buffer (50 – 75 percent), and doubling the buffer width to 15.2 m resulted in only minor additional reduction in total P losses.

The results are in agreement with the 10.7 m vegetative buffer strip recommended in the Illinois Nutrient Reduction Strategy and results from published literature that show that a 5 – 10 m buffer width is sufficient to reduce both sediment and phosphorus losses from biosolids-applied soils. Therefore, establishment of a vegetative buffer strip within the 10 m distance from surface water for land application of biosolids as required in the federal regulations (Part 503) is sufficient protection to minimize P runoff losses to surface water.

Approach for Establishing Biosolids Loading Limits. Based on findings reported in the literature and the data obtained from the studies reported here, the lower solubility and bioavailability of biosolids P compared to chemical fertilizer P is the major factor controlling the differences between the potential for P losses from agricultural land under biosolids P fertilization compared to chemical fertilizer P. This difference results in the following dynamics of potential for losses of biosolids P compared to fertilizer P:

1. At similar P application rates, the increase in water-soluble and soil-test P is lower.

2. Lower tissue P concentration and P uptake in crop.

3. Lower potential of soluble P runoff loss through surface and leaching to subsurface.

4. Lower rate of draw-down in soil test P over time.

5. Applied P is available for plant uptake over longer periods of time.

6. Lower PSI, resulting in greater potential to immobilize additional P application.

In addition, establishing vegetation in the 10-m buffer from the surface water required by federal regulation is sufficient to reduce the P from biosolids amended land to surface waters to insignificant levels. Therefore, biosolids land application rates to minimize the potential for environmental impact should not be based on cumulative biosolids or biosolids P loading alone.

The P indexing system developed by the United States Department of Agriculture and adopted by some states takes into consideration the various factors that control the potential for impact on surface water quality resulting from land application of recyclable materials such as manures. These factors include the characteristics of the P source, site characteristics, and management practices. The implementation of such P indexing systems in Illinois will be helpful in keeping land application of biosolids as an economically viable and environmentally sustainable practice for managing biosolids and sustaining agricultural production.

Recommendations for Developing Guidelines to Minimize the Environmental Impact of Biosolids Land Application. The following should be considered in developing biosolids land-application guidelines:

1. Establish a critical soil test P “environmental threshold.” This will be the maximum soil test P allowed, and any additional P applications (biosolids or chemical fertilizer) should not be greater than the P removal by the ensuing crop.

2. For all fields with soil test P greater than the agronomic P threshold (based on University of Illinois Agronomy Handbook), but lower than the “environmental threshold,” biosolids can be applied annually up to the N-based rate with the following conditions:

    a. The producer should provide, in advance, evidence of site characteristics (such as P retention properties of the soil) and management practices to demonstrate that the potential for P loss is negligible.

b. Provide data to demonstrate that the biosolids considered for land application are typical of conventionally produced biosolids (i.e. produced by anaerobic digestion; potential P retention and release characteristics).

c. Developing a site-specific management plan to ensure that P losses from biosolids-amended soil will be minimal. The management plan could include implementation of best management practices such as cover crops and establishment of vegetative buffer.

BACKGROUND

About 55 percent of the biosolids generated from the treatment of municipal wastewater in the United States are beneficially used as a fertilizer on cropland (NEBRA, 2007). Traditionally, the application rates of biosolids and other organic by-products, such as manure, on cropland are based on agronomic N requirements. The P application rates associated with N-based biosolids application rates are typically greater than crop P needs and result in a build-up of excessive soil P (Perzynski, 1994, Maguire et al., 2000 a,b; O'Connor, 2004). Excessive P in the soil can be lost from agricultural land through surface runoff and cause contamination of water bodies. Due to these concerns, federal and state regulations and guidelines are evolving rapidly, with the goal of minimizing P losses from agricultural land to surface waters (Shober and Sims, 2003; Maguire et al., 2000 a,b, 2009). Losses of P from agricultural soils receiving repeated applications of fertilizers, animal manure, biosolids, and other agricultural or food industry by-products have been identified as the largest non-point source to water bodies not only in the United States (USEPA, 2000; Carpenter et al., 1998; Kumar et al., 2009) but also in Canada (Anderson, 1998; Chambers et al., 2001) and Europe (Hooda et al., 2000).

Potential Impact of Biosolids Phosphorus on Land Application Programs

Organic by-products should be applied to meet the optimum crop nutrient requirement without allowing soil P to exceed the environmentally sensitive threshold. The P-based agronomic biosolids application rate is one approach to minimizing the imbalance and potential for excess P build-up in soils. However, compared to the conventional approach of N-based land application rates, P-based rates are very restrictive. This is because the P content of biosolids is high relative to crop P requirements. Row crops, for example corn (*Zea mays*), utilize much less P than N, while P concentrations in biosolids are typically similar to or only slightly less than N. Because P-based agronomic biosolids rates are much lower than the N-based rates, the implementation of P-based rates could make land application of biosolids operationally impractical and cost-prohibitive. Regulations that restrict application of organic by-products to less than N-based rates may encourage disposal strategies that are not based on beneficial reuse (Pierzynski and Gehl, 2005). In addition, under P-based application rates, supplemental N applications will be needed to meet crop needs. Therefore, the rules that stipulate P-based agronomic rates can make land application of biosolids unattractive and cost-prohibitive to both farmers and wastewater treatment agencies. Elliott and O'Connor (2007) recommended that a sustainable approach to biosolids management would require additional research to minimize the impact of evolving P management policies.

Since most of the wastewater treatment biosolids generated in the state of Illinois are utilized as fertilizer on land, P-based land-application rules can result in a significant increase in operating costs for wastewater treatment agencies. For example, as the largest biosolids generator in the state, the District generates approximately 160,000 dry Mg of biosolids annually, which represents about 50 percent of the biosolids produced in the state of Illinois. Over 60 percent of the biosolids produced by the District are utilized as Class B CC to fertilize cropland and a smaller amount (5 – 10 percent) as Class A lagoon-aged AD product or biosolids compost, which are used as a soil amendment or fertilizer on recreational areas in the Chicago metropolitan area. If P-based biosolids land-application rates are implemented in Illinois, it will significantly increase both the amount of land required for utilization and the distance to land-application sites. Therefore, biosolids land-application guidelines to minimize the potential for environmental impact should consider the nature and chemistry of biosolids P and its impact on plant availability and potential losses from land-application fields.

Solubility and Bioavailability of Biosolids Phosphorus

The forms of P in biosolids and physico-chemical processes that occur in soils control P solubility, plant availability, and the potential for runoff losses of P in biosolids-amended soils. Generally, conventionally treated biosolids exhibit significantly lower P solubility as compared with fertilizers (TSP) and manures (O’Connor and Elliott, 2006). The industrial wastewater contains Fe and Al, and in the conventional wastewater treatment, ferric chloride is often added as a coagulant to improve biosolids dewatering. This results in high amounts of Fe and Al oxides in biosolids, and these oxides have a high ability to fix P (McCoy et al., 1986; Van der Eijk, 1997; Shober and Sims, 2003; Elliott et al., 2006). Therefore, most of the P in biosolids is in inorganic forms and is often associated with reactive Al and Fe, which helps to immobilize P and mitigate the environmental impact of excess biosolids P (He et al., 2010; Maguire et al., 2000b). Also, P can be fixed in soil by reactive Fe and Al from biosolids, in addition to the inherent soil P fixation, leading to a low potential for P loss to water bodies. Ippolito et al. (2007) reported that oxalate extractable Fe and Al in soil, the active P-fixing compounds, increased by the biosolids application. This high P-fixing capacity leads to lower solubility of biosolids P compared to fertilizer and manure P, and it varies widely depending on the treatment processes through which the biosolids are generated (Stehouwer et al., 2000; Lu and O’Connor, 2001; Cox et al., 2002; Elliott et al., 2006). Therefore, development of biosolids application guidelines to address P environmental concerns needs to consider reactivity of biosolids-P (Elliott and O’Connor, 2007). Chinault and O’Connor (2008) recommended that the percent of water extractable P and the degree of saturation of P-sorbing sites in biosolids, or otherwise referred to as the P Saturation Index (PSI), be considered in developing P based land-application regulations and guidelines.

The P-fixing capacity of biosolids constituents affects extractability, and the fertilizer efficiency of biosolids P. McCollum (1991) reported that soil-P fixation contributed more than crop removal to the depletion of available P in soil. The size of the extractable P pool in soil as the indicator of P availability for plant P uptake and P transport to surface runoff depends on the potential availability and residual effect of P fertilizer (Torbert et al., 2002; Kumaragamage et al., 2011; Reiter et al., 2013). The soil P extractants that are commonly used to evaluate plant availability water include water, Olsen, Bray-1, and Mehlich-3 reagents. The soil test P extractants access only a fraction of the total soil P. Dodd and Mallarino (2005) reported that application of 10 mg P per kg soil is needed to raise the concentration of soil Bray-1 P by 1 mg P kg^{-1} soil in typical Iowa soils.

Soil Phosphorus Loading and Runoff Potential

Quantifying the critical soil P-loading threshold is an important step in developing nutrient management guidelines to attain water quality and crop production goals (Sharpley, 1995). Recently, there has been greater emphasis on managing land application of organic by-products on the basis of their P bioavailability and potential runoff rather than TP content (Kleinman et al., 2004; Elliott et al., 2006). Soil testing is a standard practice that is used in developing nutrient management plans (Sims, 1998), while P sorption tests (Sanyal et al., 1993) or soil phosphorus saturation (Sharpley, 1995) have also been used for evaluating environmental risks. Soil testing might be a convenient approach to identifying fields where soil P levels are excessive with respect to the potential for P runoff losses. Considerable research efforts are focused on determining the relationship between soil test P and the potential for P losses from agricultural fields. For most soils, the relationship between soil test P and the potential for P loss (as measured by dissolved or bioavailable P levels) is generally expected to be curvilinear if a sufficiently wide range in soil test P levels are evaluated. In this relationship, as soil test P increases, most of the added P is bound to the soil P sorption sites until those sites become saturated. Upon saturation, the curve relating soil test P to the potential for significant P loss approaches a “change point” at which the increase in water-soluble or bioavailable P per unit change in soil test P increases sharply.

Various approaches have been used to estimate the critical change point which correlates with an increased potential for P runoff losses. In one approach, the relationship between water extractable P and soil test P values was evaluated for fields having a wide range of soil test P or P application rates (Gburek and Sharpley, 1998). In another approach, the effect of soil test P or P loading on the concentrations of P in runoff generated through natural precipitation or through simulated rainfall was evaluated (McDowell and Sharpley, 2001; Kleinman and Sharpley, 2003). McDowell and Sharpley (2001) found that water-soluble and 0.01 $CaCl_2$ soluble P (both at 1:5 soil:solution ratio) were well correlated to dissolved P in runoff.

The critical soil P change point is not a specific P loading or soil test P value, but it is quite variable between soils and depends on many factors, which include soil texture, mineralogy, organic matter content, and pH (Kleinman et al., 2000). Heckrath et al. (1995) found that in soils amended annually with superphosphate fertilizer or farmyard manure, the change point was at approximately 60 mg kg^{-1} Olsen soil test P, above which water-soluble P levels increased sharply. This soil test P level is well above the 25 mg kg^{-1} Olsen soil test P, above which there is no further increase in the yield of most arable crops (Higgs et al., 2000). Hesketh and Brookes (2000) found that the change point varied from 10 to 119 mg kg^{-1} Olsen-P, depending on soil type, management, and hydrological conditions. McDowell and Sharpley (2001) found that the change point in two Pennsylvania soils ranged from 185 to 190 mg kg^{-1} Mehlich-3 soil test P, which is much higher than the soil test P of 50 mg kg^{-1} that is considered optimum for crop production in those soils. The results of this work are the primary basis for a single non-site specific environmental threshold adopted in the Pennsylvania P index (Sharpley et al., 2001). Nair et al. (2004) evaluated the degree of phosphorus saturation (DPS) as a tool for estimating the critical change points in sandy soils. The DPS, which is the ratio of extractable P to extractable Fe plus Al, was determined using either ammonium oxalate extraction or the Mehlich-1 and Mehlich-3 soil test methods. They found that change points in soluble P levels were associated with DPS values of 16 and 20 percent for the Mehlich-3 and oxalate methods, respectively. Alternatively, the PSI, which is expressed as a ratio of oxalate extractable P to total P sorption capacity derived from oxalate extractable Fe and Al (van der Zee et al., 1987; Khiari et al., 2000) has also been proposed as a better measure to estimate risks of P runoff.

The changes in soil extractable P over time, in high P soils due to repeated biosolids application, can be used to determine the potentially available P in applied biosolids, the residual effect, and its depletion rate over the long term. The potentially available P and depletion rate can be used to evaluate the fraction of P in biosolids as available P and the number of years of cropping required to deplete the available P (Aulakh et al., 2003).

Management Practices to Minimize Phosphorus Runoff Losses

For the past two decades, a site P indexing matrix (P-Index) approach is being evaluated and implemented in farm nutrient management plans for minimizing P loss in agricultural runoff (Lemunyon and Gilbert, 1993; Coale et al., 2002; Sims et al., 2002; Elliott et al., 2006; Kleinman et al., 2007). The index is also used to identify management practices that can be implemented at field and watershed scales to reduce the potential for P runoff to surface waters. Most states in the United States have adopted a P-Index approach to guide P-based management (Sharpley et al., 2003).

In the P-Index, source factors (such as soil test P, type of material applied, and application timing), transport factors (such as soil erosion and runoff potential), and the distance to receiving waters are used to evaluate the vulnerability of watersheds to P runoff losses. The characteristics of biosolids are significant as a source factor because biosolids P is less reactive than commercial P fertilizer, such as TSP, and P-based nutrient management rules and guidelines for the land application of biosolids should account for the differences between biosolids and other P sources. For example, in the Pennsylvania P index, the bioavailability of biosolids P is assumed to range from 20 to 80 percent (depending on treatment process), compared to P applied as inorganic fertilizer or swine slurry, for which P availability is assumed to be 100 percent. Similarly, O'Connor et al. (2004) found in a greenhouse study that the P bioavailability of most biosolids produced in a conventional activated sludge process and anaerobic digestion ranged from 25 to 75 percent relative to TSP.

Many field runoff studies have demonstrated a relationship between soil test P and runoff P concentrations (Sharpley, 1995; Pote et al., 1999; Tarkalson and Mikkelsen, 2004), and several micro-plot rainfall simulation studies have documented P losses from applied amendments (Guidry et al., 2006). However, these research efforts are labor intensive, time consuming, and often limited by seasonal timeframes. Consequently, simulated rainfall studies using runoff boxes have been used successfully as an alternative means of obtaining soil P loss information without the seasonal limitations and confounding variables associated with *in situ* field studies (Allen et al., 2006; Guidry et al., 2006; McDowell et al., 2007).

Although several studies have been conducted to quantify P losses in runoff following incorporation or surface application of various P sources, most studies have been focused on manure or other agricultural or food processing by-products, and only a few studies have focused on biosolids (Bundy et al., 2001; Elliott et al., 2005; O'Connor and Elliott, 2006; Agyin-Birikorang et al., 2008). The results of these studies show wide variability in runoff P losses due to not only the differences in bioavailable P in the biosolids, the wastewater treatment processes employed in the generation of these biosolids, and the presence of other constituents, like Fe and Al, but also management practices that affect the losses of biosolids P.

RATIONALE

In response to the increasing concerns of the potential for P build up in soil due to land application of biosolids, the District began discussions with the IEPA to conduct studies to generate information that can be used to formulate guidelines for managing land application of biosolids to minimize the potential for P loss to surface waters in the state of Illinois. As part of this process, the IEPA identified the following five areas of interest that would be useful to the agency for developing land-application guidelines for biosolids in Illinois. Based on these five interests, the overall objectives of the study were to evaluate:

1. Availability of biosolids P.

2. Residual availability of biosolids P.

3. Effect of biosolids incorporation on reducing P runoff.

4. Width of buffer zone required to limit P runoff.

5. Whether a phosphorus index system is more appropriate than cumulative loading rates for setting biosolids loading limits.

In collaboration with the IEPA, Dr. George O'Connor, of the University of Florida, and Dr. Herschel Elliott, of Pennsylvania State University, the Metropolitan Water Reclamation District of Greater Chicago (District) conducted five separate studies to address the five overall objectives. The approach and results of the five studies are summarized in the following five chapters of this report:

- Chapter 1 – Bioavailability of Biosolids Phosphorus – A Greenhouse Study

  This study addresses Objectives 1 and 2.

- Chapter 2 – Bioavailability of Biosolids Phosphorus – A Field Study

  This study addresses Objectives 1 and 2

- Chapter 3 – Potential for Phosphorus Losses in Surface Runoff From Soil Amended with Repeated and Long-Term Biosolids Applications

  This study addresses Objective 5.

- Chapter 4 – Using Simulated Rainfall to Determine Phosphorus Loss in Surface Runoff from Biosolids-Amended Soil

This study addresses Objective 3.

- Chapter 5 –Phosphorus Runoff Losses in Biosolids Amended-Soil and Control by Vegetated Buffer Strips

This study addresses Objective 4.

The results obtained from these studies, and a review of the literature were used to address Objective 5.

CHAPTER 1

BIOAVAILABILITY OF BIOSOLIDS PHOSPHORUS – A GREENHOUSE STUDY

Abstract

An estimate of the bioavailability of biosolids P is essential for developing P-based biosolids land-application guidelines. A greenhouse study was conducted to determine the bioavailability of P in Class B CC biosolids and Class A AD biosolids. The biosolids and TSP were applied to a P-deficient Immokalee fine sand to achieve seven targeted P rates (0 to 300 mg P kg^{-1}). A 15-cm layer of the amended soil was placed on top of a 23-cm unamended soil layer in pots in the greenhouse and cropped for 18 consecutive 35-day cropping cycles of alternating crops of wheat (*Triticum aestivum* L.) and perennial ryegrass (*Lolium perene* L). The response of WSP to the P rate was over six times greater in TSP than in the biosolids treatments. Bray-1 P in all treatments increased with the P rate, and the response was defined by a single slope (0.598) for the AD and CC biosolids and a higher slope (0.739) for TSP. The decrease in soil P concentrations over time was slower in biosolids than in TSP treatments. At the end of the study, Bray-1 P in the 0 - 15 cm soil layer, as a percentage of the concentration in the amended soil before cropping, ranged from 20 to 44 percent in the biosolids treatments and only 3 to 9 percent in the TSP treatments. This showed that biosolids P is less bioavailable and less prone to leaching than TSP. Short-term P bioavailability (P uptake in the first three crops), as a percentage of TSP, was 43 percent for AD and 28 percent for CC biosolids. In the long term, bioavailability at low P rates increased to 85 percent for AD and 61 percent for CC biosolids due to the slow release of biosolids P over time. The data show that the bioavailability of biosolids P is lower than TSP, and agronomic P rates for these biosolids should be greater than for chemical fertilizer.

Objectives

The objectives of this study were:

1. To compare AD and CC biosolids and TSP with respect to soil test P build up resulting from the applied P and draw down due to P removal by cropping.

2. To determine the short-term and long-term (residual) bioavailability of P in AD and CC biosolids relative to fertilizer P.

Materials and Methods

The P sources used in this study were AD and CC biosolids and TSP fertilizer. The biosolids used in this study were AD and CC biosolids produced after mesophilic anaerobic digestion at the District’s Stickney Water Reclamation Plant (WRP). The biosolids were collected from paved beds where the AD biosolids (53 percent solids) are dried and where the CC biosolids (18 percent solids) are held temporarily before utilization. The biosolids were screened through a 1-cm mesh, without additional drying, and stored at 4°C. The soil was a P-deficient acidic Immokalee sand (sandy, siliceous, hyperthermic Arenic Alaquods) obtained from Florida. A P-deficient soil was selected to generate response curves covering the range from P deficiency to excessive P to adequately evaluate bioavailability. Little or no difference between P sources and response to P rates is expected in soil having excessive P or high P-sorbing capacities (Sakar and O'Connor, 2004). The Immokalee sand was selected because analysis on the P chemistry has been determined, and several studies are reported on the P bioavailability and mobility in this soil (Elliott et al., 2002; O'Connor et al., 2004; Oladeji et al., 2008a, b; Miller and O'Connor, 2009)

Greenhouse Study. The AD and CC biosolids and the TSP used as P sources in the study were weighed based on their total P contents to establish four replications of six P rates targeted at 25, 50, 100, 150, 200, 300 mg P kg^{-1} (56, 112, 224, 356, 448, and 672 kg P ha^{-1}) and blended with 7.1-kg portions of the soil. An unamended control was also included. The 300 mg P kg^{-1} soil is the typical rate of P applied at the average N-based biosolids rate of 22.4 Mg ha^{-1} used in the District's farmland application program. The other rates, including the typical P-based rate (25 mg P kg^{-1} soil), were included to generate relative bioavailability response curves and to evaluate the drawdown of soil P built up through multiple years of N-based biosolids application rates. Fertilizer in the form of 2 g potassium-magnesium-sulfate ("Sul-Po-Mag": 22 percent sulfur (S), 18 percent potassium (K), and 11 percent Mg and ammonium nitrate (NH_4NO_3-N) was added. The amount of N was based on the amounts of plant available N supplied by the various biosolids to achieve the N application rate of ~448 kg N ha^{-1} in all treatments. The amended soils were placed into plastic bags, moistened with de-ionized water to approximately 80 percent of field capacity (FC), kept in the laboratory at room temperature for two weeks, and intermittently mixed in the plastic bag during this period to facilitate equilibration of treatments with the soil.

Portions (9-kg) of the unamended Immokalee soil were added to plastic pots (38-cm high, 18-cm diameter top) to create an unamended subsoil layer of approximately 23 cm. Reverse osmosis (RO) water was added slowly to moisten the soil to approximately 80 percent of FC. A 100-g sample of the treated soil was removed from the bags and air-dried for analysis. The bags of treated soil were poured into the pots on top of the unamended soil layer to create a 15-cm amended layer.

The pots were arranged on the greenhouse bench as a 3 (P sources) x 6 (P rates) factorial plus a control in a completely randomized block design consisting of four blocks. Wheat (*Triticum aestivum* var. Patton) was sown in the spring of 2004 and then thinned to 15 plants per pot after germination. To maintain adequate soil moisture and minimize the drainage, the moist (~80 percent FC) pots were weighed at the beginning of the study and RO water added daily based on the estimated moisture loss determined by weighing the pots periodically. Any drainage was collected in a saucer at the bottom of the pots and poured back into the pots to minimize leaching losses from the pots. At 35 days after germination, the wheat foliage was clipped at 2.5 cm above the soil surface, and the remaining stubble was left to regrow for a total of four crops clipped every 35 days. After the fourth wheat crop, the pots were seeded with ryegrass (*Lolium perene* var. Pleasure) for another sequence of four crops clipped every 35 days. This sequence of four clippings of wheat and ryegrass was alternated four times, plus two additional foliage clippings of wheat. This resulted in a total of 18 crops for the entire study. The cropping sequences were scheduled so that growing periods were during May – November for wheat and December – May for ryegrass. In Crops 3 and 4 of the first sequence of wheat cropping, foliage growth was much less than in Crops 1 and 2. Therefore, for the remainder of the study, reseeding was done after every two crops.

Soil samples of 1.2-cm cores were collected from the amended surface (0- to 12.5-cm) and unamended subsurface (12.5-cm to bottom) of the pots. Sampling was done before each seeding, which was after Crop 4 of the first sequence of wheat and after every two crops thereafter. However, subsoil samples were not collected at the sampling events after Crops 4 and 14. After sampling, the soil on the walls of the subsurface holes was perturbed to fill the holes and minimize surface soil mixing with subsurface soil.

After every four crops, 2 g Sul-Po-Mag and 1.5 g N (450 kg N ha^{-1}) as NH_4NO_3 were added to each pot by blending into the surface soil (10-cm). This fertilizer regime supplied excess N, K, Sulfur, and Mg to minimize the effects of the varying rates of these nutrients supplied by the biosolids treatments.

Analysis of Soil and Plant Tissue. Samples of the biosolids and soil used in the study were air-dried and sieved (2-mm), then analyzed for total P, Fe, Al, Ca, Mg, manganese (Mn), potassium chloride-extractable ammonia N (NH_3-N), nitrate N (NO_3-N), and total Kjeldahl N (TKN). Bray-1 P and Mehlich-3 extractable P were determined in all the surface soil samples collected during the greenhouse study and selected subsurface soil samples. Water-soluble phosphorus analysis was done using a 1:100 solid:water ratio (Wolf et al., 2005) and total P by persulfate digestion (Greenberg et al., 1998).

The wheat and ryegrass tissues were washed with de-ionized water and then dried at 65C° and weighed to determine dry matter (DM) yield. The dried tissue was ground to pass a 20-mesh and extracted by persulfate digestion. The P concentrations in soil and plant digests and in soil extracts were determined colorimetrically (Murphy and Riley, 1962).

Data Analyses. Foliage P uptake was calculated as the product of DM yield and tissue P concentration. Analysis of variance on foliage tissue P concentration, cumulative DM yield, and cumulative P uptake at the end of each crop and extractable soil P concentrations were analyzed by PROC GLM SAS. Data for the first three crops (Crops 1 – 3) were regarded as representing the short-term bioavailability, and data for Crop 1 to the crop in which soils became P-deficient were regarded as representing long-term (residual) bioavailability. Regression analysis was done to evaluate the effect of the P rate on crop tissue P concentrations and P uptake and on soil extractable P concentrations (Bray-1, Mehlich-3, and WSP using SigmaPlot®).

Results and Discussion

Biosolids Characteristics. The chemical characteristics of AD and CC biosolids are similar, except for differences in N species, which are due mainly to lagoon aging and drying of AD biosolids (Table 1-1). Because of this additional processing of AD biosolids, mineralization

TABLE 1-1: SELECTED PROPERTIES OF THE CENTRIFUGE CAKE AND AIR-DRIED BIOSOLIDS USED IN THE STUDY

Parameter	Biosolids Type	
	AD	CC
	---------- $g\ kg^{-1}$ ----------	
OC	221.5	174.4
TKN	21.1	41.8
	---------- $mg\ kg^{-1}$ ----------	
NH_3-N	493	7,245
NO_3-N	764	5.7
WSP[1]	207	215
	----------Total, $g\ kg^{-1}$ ----------	
P	19.9	20.1
Al	22.6	20.9
Fe	19.1	13.8
Mn	0.52	0.49
Ca	41.8	31.8
Mg	18.4	11.1
	----------Oxalate-Extractable, $g\ kg^{-1}$ ----------	
P	18.6	17.2
Al	12.8	13.2
Fe	12.2	9.0
PWSP[2]	1.11	1.06
PSI[3]	0.87	0.86

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[1] Water-soluble P (1:100 solid:water ratio).

[2] PSWP = Percent WSP = WSP/total P x 100.

[3] PSI = phosphorus saturation index = [Pox]/[Alox + Feox].

resulted in lower TKN and NH_3-N and greater NO_3-N than in the CC biosolids. However, organic carbon was unexpectedly greater in AD than in CC biosolids.

Total P in both biosolids was similar (Table 1-1) and was within the range for conventionally produced biosolids (USEPA, 1995). Most of the P was in the oxalate-extractable form, and oxalate P was slightly greater in AD than in CC biosolids. O'Connor et al. (2004) found that over 90 percent of biosolids P is in the oxalate-extractable form. Oxalate extractable Al and Fe in both biosolids were similar.

The oxalate-extractable (ox) data in Table 1-1 were used to calculate the PSI (PSI = [Pox]/[Alox + Feox] for evaluating lability of biosolids P (Elliott et al., 2002). The PSI in both biosolids was similar and is reflected in the similarity of their WSP contents. Water-soluble P as a percent of total P (PWSP) was similar for both biosolids. The similarities in the P chemistries of the biosolids suggest that bioavailability of P should be similar.

Effectiveness of Biosolids on Build Up of Soil Test Phosphorus. Based on the analysis of TP of the biosolids and TSP-amended soil treatments, the difference between the targeted and actual application rates varied among the treatments (Table 1-2). The largest magnitude difference between the targeted and actual P rates occurred at the highest AD biosolids rate (300 mg P kg^{-1} targeted vs. 350 mg P kg^{-1} actual). The method used for TP analysis has relatively high accuracy and precision (Greenberg et al., 1998). In addition, the complete recovery of total P by analysis was verified by analyzing the samples, together with an internal soil standard, which was calibrated with a certified reference municipal sewage sludge standard (CRM007-040) obtained from the National Institute of Standards. Therefore, we considered the TP analysis of the treated soils to more reliably represent the actual amount of P applied than the targeted P rates. The differences between actual and targeted P application rates are attributed primarily to inadequate control on the moisture content during the weighing of the soil and biosolids to establish the treatments. Therefore, in evaluating the effect of P rates, TP in the treatments minus the control were used as P rates instead of the targeted P rates, except in cases where a targeted P rate is used to designate a treatment level for all three P sources.

At the beginning of the greenhouse study, the Bray-1 P and WSP in the treated soil increased with the P rate (Table 1-2). The Bray-1 P correlated well with Mehlich-3 P (Mehlich-3 P = 1.64 + 1.14 x Bray-1 P, $r^2 = 0.99$; data not shown). This approximately 1:1 relationship between Bray-1 P and Mehlich-3 P indicates that both methods are equivalent P soil tests for this soil. Phosphorus fertilizer recommendations in Illinois are based on either of the two soil test methods. The increase in Bray-1 P in response to applied P was linear, with a single slope of 0.598 for the AD and CC biosolids and a greater slope 0.739 for TSP (Figure 1-1). The slope of the line in these relationships is a measure of the fraction of applied P that is extractable by the Bray-1 P procedure and the effectiveness of the P sources in increasing the levels of Bray-1 P extractable P. These relationships indicate that based on the assumption that the 15-cm plough layer of field soil weighs 2.2×10^6 kg ha^{-1} (2 million pounds per acre), the P application required to increase Bray-1 P by 1 mg kg^{-1} in this sandy soil is about 2.9 kg ha^{-1} for TSP and 3.7 kg ha^{-1} for the biosolids. The increase in Bray-1 P in response to applied P is relatively high and is due to the low P retention capacity of the sandy soil. The extractability of applied P is greater in sandy soil than in loam or clayey soil (Smith et al., 2002). Schroder et al. (2008) found that in a

TABLE 1-2: TOTAL PHOSPHORUS IN IMMOKALEE SAND AMENDED WITH AIR-DRIED AND CENTRIFUGE CAKE BIOSOLIDS AND TRIPLE SUPERPHOSPHATE FERTILIZER AT SEVEN PHOSPHORUS RATES AND BRAY-1 PHOSPHORUS AND WATER-SOLUBLE PHOSPHORUS IN THE AMENDED SURFACE SOIL IN POTS BEFORE AND AFTER 18 CONSECUTIVE 35-DAY CROPPING CYCLES WITH WHEAT AND RYEGRASS ROTATION

P Source	Targeted P Rate	Actual[1] P Rate	Total P	Before Cropping[2] Bray-1 P	Before Cropping[2] WSP	After Crop 18[2] Bray-1 P		After Crop 18[2] WSP	
	mg kg-1					mg kg-1	%[3]	mg kg-1	%[3]
Control	0	0	21 ± 3.1[4]	2.5 ± 0.6	0.9 ± 0.2	0.7 ± 0.1	26	0.7 ± 0.1	73
AD	25	20	41 ± 7.1	15.5 ± 3.4	3.6 ± 1	3.1 ± 0.6	20	1.1 ± 0.2	31
	50	38	59 ± 4.4	23.7 ± 2.3	5.0 ± 0.5	5.5 ± 0.8	23	1.5 ± 0.3	30
	100	136	157 ± 16	73.6 ± 2.9	14.9 ± 2.5	20.1 ± 3.3	27	2.6 ± 0.4	17
	150	190	210 ± 14	102.9 ± 8.6	18.5 ± 1.2	45.1 ± 4.8	44	5.7 ± 0.7	31
	200	237	258 ± 11	128.3 ± 9.2	24.2 ± 1	67.2 ± 11.0	52	8.2 ± 0.7	34
	300	350	371 ± 20	225.9 ± 11.1	40.6 ± 2.8	116.6 ± 6.2	52	9.8 ± 1.1	24
CC	25	27	48 ± 8.9	15.4 ± 1.6	3.4 ± 1.4	3.5 ± 0.4	23	1.7 ± 0.9	49
	50	47	68 ± 14	28.4 ± 6.9	6.1 ± 2.1	6.8 ± 1.0	24	1.5 ± 0.2	25
	100	69	89 ± 26	35.4 ± 6.2	8.0 ± 1.1	14.9 ± 3.0	42	2.7 ± 0.6	34
	150	160	181 ± 13	92.4 ± 5.4	11.1 ± 0.8	34.3 ± 3.9	37	3.9 ± 0.3	35
	200	214	235 ± 28	129.4 ± 19.6	13.5 ± 0.7	52.7 ± 8.3	51	6.3 ± 1.0	47
	300	268	289 ± 19	155.1 ± 10.4	17.2 ± 2.3	81.8 ± 2.9	53	7.3 ± 0.8	42

TABLE 1-2 (Continued): TOTAL PHOSPHORUS IN IMMOKALEE SAND AMENDED WITH AIR-DRIED AND CENTRIFUGE CAKE BIOSOLIDS AND TRIPLE SUPERPHOSPHATE FERTILIZER AT SEVEN PHOSPHORUS RATES AND BRAY-1 PHOSPHORUS AND WATER-SOLUBLE PHOSPHORUS IN THE AMENDED SURFACE SOIL IN POTS BEFORE AND AFTER 18 CONSECUTIVE 35-DAY CROPPING CYCLES WITH WHEAT AND RYEGRASS ROTATION

	Targeted	Actual[1]		Before Cropping[2]		After Crop 18[2]			
P Source	P Rate	P Rate	Total P	Bray-1 P	WSP	Bray-1 P		WSP	
	----------------	mg kg^{-1}	----------------			mg kg^{-1}	%[4]	mg kg^{-1}	%[4]
TSP	25	27	48 ± 4.5	19.7 ± 1.3[2]	14.7 ± 2	1.7 ± 0.5	9	0.6 ± 0.1	
	50	59	80 ± 14	35.6 ± 4.5	30.4 ± 4.6	1.5 ± 0.2	4	0.7 ± 0.3	2
	100	85	105 ± 14	65.2 ± 7.0	58.2 ± 2.9	2.1 ± 0.3	3	1.0 ± 0.2	2
	150	134	155 ± 12	98.5 ± 7.2	92 ± 5.8	3.6 ± 0.9	4	2.1 ± 0.8	2
	200	185	206 ± 18	125.2 ± 9.7	139.5 ± 6.5	6.1 ± 1.5	5	3.6 ± 1.0	3
	300	256	277 ± 18	194.9 ± 15	167.2 ± 16.1	8.2 ± 1.7	4	4.3 ± 1.1	3

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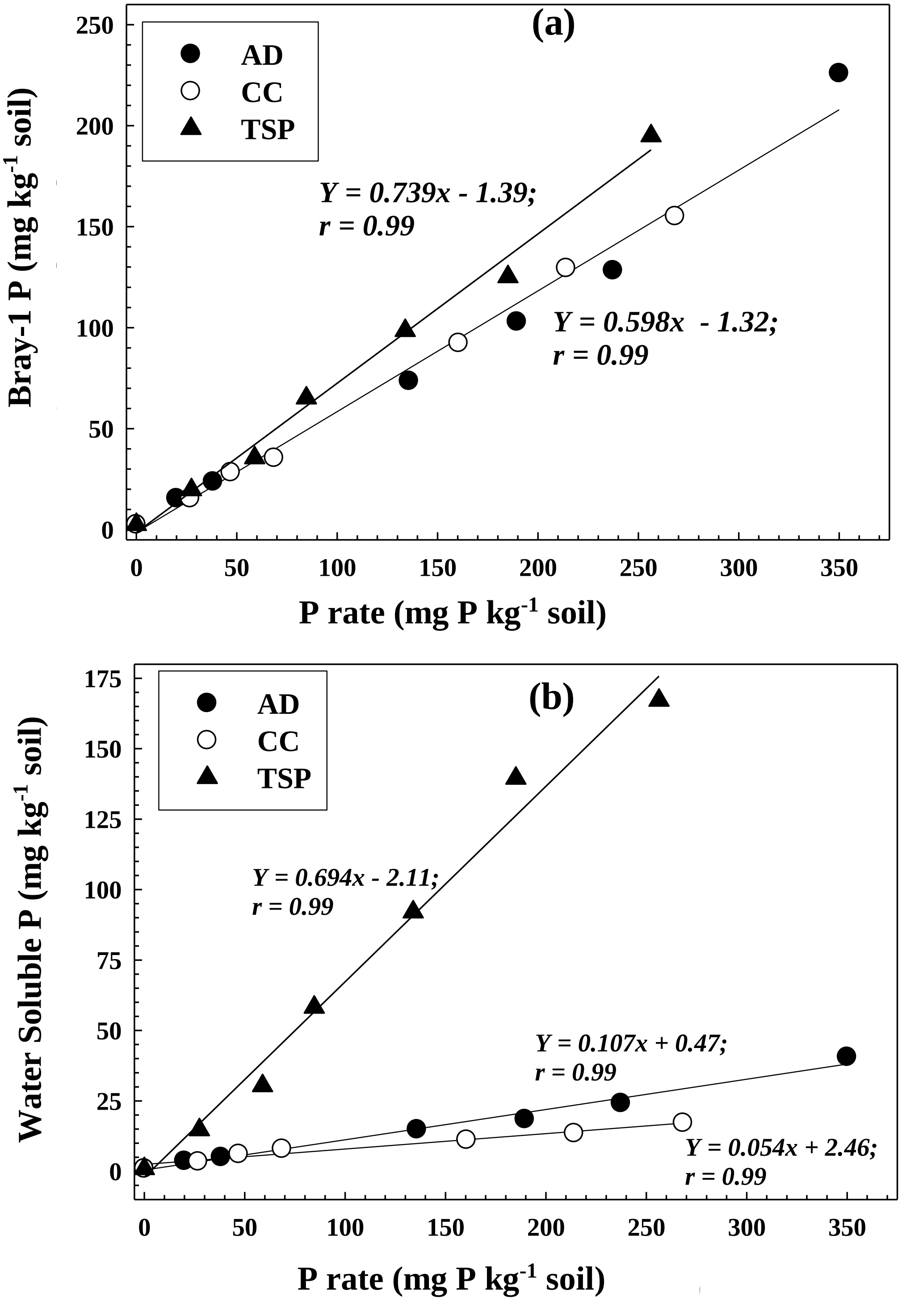
[1] Actual P rate = total P in treatment minus control.

[2] Effect of all variables (P Source, P Rate, and P Rate x P Source) highly significant ($p<0.001$).

[3] Bray-1 P and WSP expressed as a percentage of the concentrations in the treated soil before cropping.

[4] Means ± standard deviation.

FIGURE 1-1: BRAY-1 PHOSPHORUS AND WATER-SOLUBLE PHOSPHORUS IN SURFACE SOIL TREATED WITH VARYING RATES OF AIR-DRIED AND CENTRIFUGE CAKE BIOSOLIDS AND TRIPLE SUPERPHOSPHATE FERTILIZER PHOSPHORUS BEFORE CROPPING IN THE GREENHOUSE



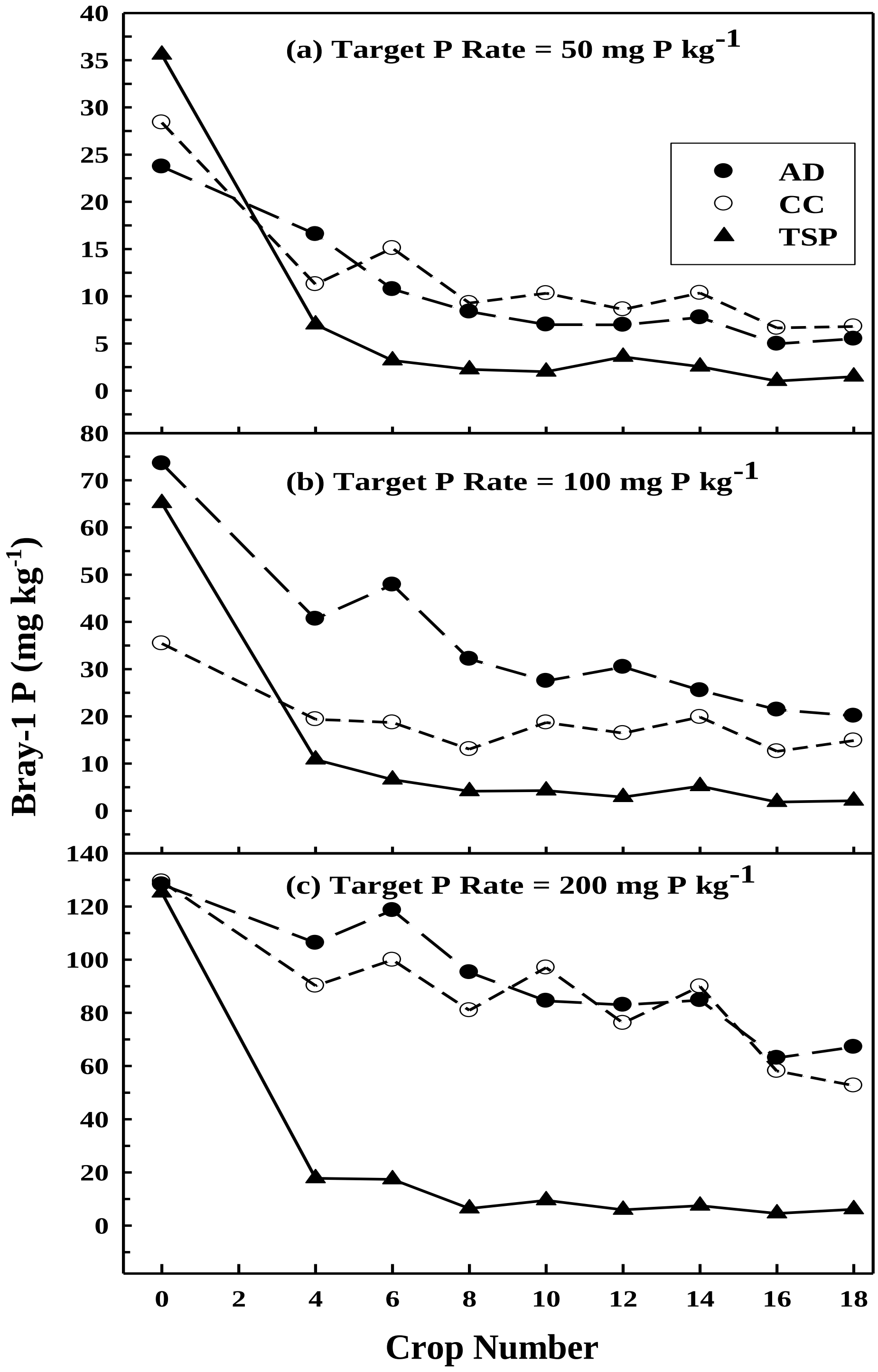
Norge loam soil, approximately 33 kg P ha^{-1} biosolids P was required to increase Mehlich-3 P by 1 mg kg^{-1}. In a study conducted on 17 noncalcareous soils, Haden et al. (2007) showed that TSP and liquid dairy manure had a similar fertilizer effectiveness (approximately 9.8 kg P ha^{-1} to increase Mehlich-3 P by 1 mg P kg^{-1}). The relationship in the sandy soil in our study also shows that the effectiveness in building up Bray-1 P soil test P for both the AD and CC biosolids (3.7 kg ha^{-1}) in the sandy soil relative to TSP (2.9 kg ha^{-1}) is about 78 percent.

The effect of the P rate on WSP was less than the effect on Bray-1 P and varied among the P sources (Figure 1-1b). Water-soluble P increased linearly, and the slope was much greater for TSP (slope of 0.69) than for biosolids P (0.10 and 0.05 for AD and CC, respectively). The large difference between the effects of the P rate on Bray-1 P and WSP is most likely because the Bray-1 P method is much more effective than the WSP method in extracting the P bound in solid phases such as oxides of Al and Fe (Kuo, 1996). We would have expected the effect of AD and CC biosolids on WSP to be more similar than observed because the P chemistries of both biosolids are similar (Table 1-1).

Rate of Drawdown of Soil Test Phosphorus. The rate of decline in extractable P in soil over time in response to crop removal and soil processes following application of fertilizers and other P sources is important in managing soil P for optimum crop production. Bray-1 P soil test P was determined on the amended surface soil prior to cropping after the fourth crop and after every two crops thereafter. The decline in Bray-1 P in the amended surface soil resulted primarily through crop uptake and leaching into the unamended subsoil. During cropping, Bray-1 P initially decreased quickly with time, but the rate of decrease was slower with further cropping, as shown for the 50, 100, and 200 mg P kg^{-1} targeted P rates (Figure 1-2). The decrease in the TSP treatments over time was greater than in the biosolids treatments. During the slow period, Bray-1 P followed a downward fluctuating trend. The same fluctuating trend was observed for WSP in the amended surface soil (data not shown). Read et al. (2007) reported a fluctuating decline in Mehlich-3 P over a 25-year period in high soil test P soil continuously cropped with Bermuda grass (*Cynodon dactylon*) and ryegrass. The authors attributed the increases that occurred during the period of the fluctuation to P release from the mineralization of the fibrous root system remaining in the soil after harvesting foliage. In a field study, van der Salm et al. (2009) observed seasonal fluctuation of extractable P in P-rich surface soil cropped over a five-year period to reduce soil P by phytoextraction. Pederson et al. (2002) showed that the P concentration in root tissue of wheat and ryegrass is generally less than 10 percent of the leaf tissue P concentration. Root tissue was not harvested and analyzed in our study, but it probably adds to labile soil P. The fluctuation can also be attributed to variations in the physico-chemical processes controlling solubility and extractability of biosolids P over time.

Following Crop 18 (end of the study), extractable P increased with the P rate (Table 1-2). At each targeted P rate, extractable P was greater in the biosolids treatments than in the TSP treatments. Except in some of the TSP treatments (25 – 100 mg kg^{-1} targeted P rates), Bray-1 P and WSP levels in the treated soil were greater than in the unamended soil before cropping (Table 1-2). In the biosolids treatments, extractable P at the end of the study, expressed as a fraction of the levels in the treated soil before cropping (Table 1-2), increased with the P rate, ranging from 20 percent to 53 percent for Bray-1 P and from 17 percent to 49 percent for WSP (Table 1-2). For TSP, extractable P as a fraction of the levels in the treated soil before cropping was lower than for the biosolids, ranging from 3 to 9 percent, with no trend among the rates. This

FIGURE 1-2: BRAY-1 PHOSPHORUS IN SURFACE SOIL AMENDED WITH THREE TARGETED PHOSPHORUS RATES OF AIR-DRIED AND CENTRIFUGE CAKE BIOSOLIDS AND TRIPLE SUPERPHOSPHATE FERTILIZER AT INTERVALS DURING 18 CONSECUTIVE 35-DAY CROPPING CYCLES WITH WHEAT AND RYEGRASS ROTATION



lower fraction for TSP suggests that extractable P in the soil was depleted. Eghball et al. (2003) showed that in manure-amended soils having very high levels of soil test P, the rate of decline of soil test P was greater in those soils having higher soil test P values than in those soils where soil test P is close to the initial (unamended) soil test levels. The sandy soil used in our study has a low P-binding capacity, which resulted in high extractability of the applied P (Figure 1-1) compared to clayey, high-binding soils. The highly extractable forms of applied P are also readily available for plant uptake and leaching.

The change in extractable P in the unamended subsoil was measured to evaluate the contribution of P leaching to decline in extractable P in the amended surface layer. Following Crop 18, Bray-1 P and WSP in the unamended subsoil increased with the P rate (Table 1-3), indicating that applied P leached from the amended surface soil. Some inadvertent mixing of the amended surface soil with the unamended subsurface at soil sampling events and backfilling of holes resulting from the removal of soil cores probably made a small contribution to this increase in subsoil P.

The effect of the P rate on Bray-1 P was similar for the three P sources. However, this similarity does not indicate that similar masses of P leached from each P source during the study. Because of the higher extractability of the TSP P (Figure 1-1), it is likely that earlier in the study, P leaching was greater from TSP than from biosolids, and a portion of the P that leached from TSP into the unamended subsurface was taken up by the crop as the amended surface became depleted in P. Other studies have shown that the efficiency of P removal by crops increases as soil becomes P-deficient (Eghball et al., 2003; Pant et al., 2004).

The contribution of P leaching and crop P uptake is demonstrated by the changes in extractable P in the amended surface soil and the subsoil during the study. In the surface soil, there was a faster decline in Bray-1 P with time in the TSP than in the biosolids treatments (Figure 1-2). Following Crop 6, Bray-1 P and WSP in the subsoil of the treated soils were greater than in the untreated soil and were greater in the TSP than in the biosolids (Table 1-3). From Crop 6 to Crop 18, Bray-1 P and WSP levels declined sharply in the TSP treatments, but there was very little change in the biosolids treatments. This decrease in extractable P in the TSP treatments indicates that the P leached before Crop 6 was being depleted by crop uptake. Leaching out of the pots contributed minimally to the decrease in subsoil P because the moisture content of the soil was managed to minimize drainage from the pots, and any leachate was returned to the surface of the pots. Subsoil WSP was lower for biosolids than for TSP at all treatment levels following Crop 6 and most treatment levels following Crop 18 (Table 1-3). Other studies have shown less P leaching in soil amended with biosolids than with TSP (Elliott et al., 2002. Alleoni et al., 2008; Oladeji et al., 2008a).

Critical Concentration of Phosphorus in Plant Tissue. Determining the critical tissue P concentration is essential for comparing treatments with respect to sufficiency levels of tissue P for optimum crop growth. In this study, the tissue P level that sustains optimum DM yield is considered the critical tissue concentration. Below the critical concentration, plants continue to absorb P, but the soil is considered P-deficient, and P fertilization is required to sustain optimum plant growth and yield. Therefore, the critical plant foliage P concentration to maintain near the maximum DM yield under the greenhouse conditions was estimated by evaluating the relationship between the foliage P concentration and relative DM yields in the first clipping of

TABLE 1-3: BRAY-1 PHOSPHORUS AND WATER-SOLUBLE PHOSPHORUS IN UNAMENDED SUBSURFACE SOIL IN POTS AMENDED WITH AIR-DRIED AND CENTRIFUGE CAKE BIOSOLIDS AND TRIPLE SUPERPHOSPHATE FERTILIZER AT SIX PHOSPHORUS RATES AFTER THE 6th AND 18th CONSECUTIVE 35-DAY CROPPING CYCLES WITH WHEAT AND RYEGRASS ROTATION

	Actual	After Cropping Cycle 6[1]		After Cropping Cycle 18[1]	
P Source	P Rate	Bray-1 P	WSP	Bray-1 P	WSP
		------------------ mg kg^{-1} ------------------			
Control	0	3.2 ± 0.3[2]	1.4 + 0.2	1.8 ± 0.4	1.5 ± 0.3
AD	20	5.0 ± 0.4	1.8 + 0.3	4.3 ± 0.4	2.2 ± 0.2
	38	6.8 ± 0.5	2.5 + 0.8	5.7 ± 0.5	2.9 ± 0.3
	136	18.9 ± 2.6	3.7 + 0.3	11.6 ± 1.4	3.3 ± 0.6
	190	25.1 ± 6.1	4.3 + 0.4	23.5 ± 3.6	4.6 ± 0.2
	237	38.9 ± 9.7	6.5 + 2.6	35.4 ± 8.5	6.7 ± 0.7
	350	57.7 ± 9.6	7.4 + 0.8	46.5 ± 4.5	6.4 ± 0.4
CC	27	4.8 ± 0.4	2.3 + 0.1	4.9 ± 0.7	2.5 ± 0.3
	47	7.4 ± 1.2	3.0 + 0.3	6.3 ± 0.4	2.9 ± 0.3
	69	9.0 ± 2.3	3.3 + 0.7	8.9 ± 1.3	3.5 ± 0.4
	160	21.9 ± 2.9	4.5 + 0.7	24.1 ± 3.8	4.9 ± 0.4
	214	27.5 ± 5.6	4.8 + 1.0	33.0 ± 4.6	5.1 ± 0.3
	268	30.7 ± 8.0	4.1 + 0.4	53.7 ± 4.2	5.7 ± 0.5
TSP	27	5.3 ± 0.6	3.4 + 0.6	3.5 ± 0.7	2.4 ± 0.2
	59	8.5 ± 1.0	4.7 + 1.3	4.5 ± 1.0	2.8 ± 0.6
	85	19.7 ± 3.2	13.6 + 1.5	7.7 ± 1.5	4.7 ± 0.8
	134	33.6 ± 4.9	25.3 + 4.7	15.0 ± 2.6	9.3 ± 1.5
	185	47.9 ± 2.4	44.8 + 5.7	22.0 ± 4.9	14.5 ± 4.0
	256	69.6 ± 5.4	63.8 + 4.5	36.0 ± 8.0	25.3 ± 6.6

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[1] Effect of all variables (P Source, P Rate, and P Rate x P Source) highly significant ($p<0.001$).

[2] Means ± standard deviation.

the first three crop cycles of the TSP treatments, which included both wheat (Crop 1) and ryegrass (Crops 5 and 7). The three crops were selected as they were the first clipping from seeding, and they grew more vigorously than the succeeding regrowth. To estimate the critical P concentration, the data were fitted to a linear-plateau model using SigmaPlot® two-segment piece-wise linear regression model. The data (Figure 1-3) show that using the 95 percent relative DM yield as the optimum yield, the critical foliage P concentration is approximately 2.6 g P kg^{-1} (DM basis). This critical concentration is based on the assumption that no other essential nutrient is limiting and that the rate of foliage growth is directly related to crop yield potential under the conditions of the study. This critical level was within the range of 2.5 to 5.0 g kg^{-1} tissue P for growth stage 10.1 wheat (Westfall et al., 1990).

Short-Term Phosphorus Bioavailability. We define P bioavailability in this study as the response of tissue P concentration and cumulative P uptake in foliage to applied P. Short-term bioavailable P was defined as P uptake in the first three crops. Tissue P concentrations (Table 1-4) in the first three crops were greater than the critical tissue P concentration of 2.6 g kg^{-1} (Figure 1-3), except in the control and in Crops 2 and 3 of the lowest biosolids treatment rates. In all treatments, tissue P concentrations decreased consistently from Crop 1 to Crop 3 at all P rates and were in the order TSP>AD>CC. At the highest TSP rate, tissue P concentration in Crop 1 was almost ten times the critical concentration (Table 1-4), indicating luxury P consumption. Gaston et al. (2003) reported tissue P concentrations up to 7.3 g kg^{-1} in ryegrass grown in high soil test P soil in the greenhouse.

For all three P sources, short-term bioavailable P increased with the P rate (Table 1-4) and was in the order TSP>AD>CC. This difference between short-term bioavailable P in TSP and biosolids correlates with the differences in soil test P over time (Figure 1-2), which showed that the decline in Bray-1 P with cropping was greater in TSP than in the biosolids. For all three P sources, short-term bioavailable P uptake increased sharply with the P rate and tended to level at a maximum P uptake response at the higher P rates. The response to the P rate was well described by the following exponential rise to Maximum Two-Parameter model (Figure 1-4):

$Y = a \text{ x } (1-e^{-bx})$ where,
a = maximum P uptake (mg P pot^{-1})
b = rate factor and
x = P rate (mg kg^{-1} soil)

Based on the model results, the maximum potential P uptake for the P sources was 300, 127, and 83 mg P pot^{-1} for TSP, AD, and CC biosolids, respectively. This maximum P uptake potential is within the P rate (~300 mg P kg^{-1} soil) associated with N-based agronomic application rates of typical District biosolids. By comparing the biosolids treatment to TSP based on the maximum P uptake potential, relative bioavailabilities of AD and CC biosolids are 43 percent and 28 percent of TSP, respectively. The bioavailability values are within the range of 41 to 82 percent (Oladeji et al., 2008a) and 25 to 75 percent (defined as “moderate” bioavailability; O’Connor et al., 2004) observed for conventionally produced biosolids. At the soil test P of 30 mg P kg^{-1} recommended for near maximum yield of grain crops in Illinois, short-term P uptake predicted by the model is 116, 74, and 57 mg P kg^{-1} for TSP, AD, and CC biosolids, respectively. These represent relative

FIGURE 1-3: RELATIONSHIP BETWEEN DRY MATTER AND FOLIAGE PHOSPHORUS IN 35-DAY WHEAT AND RYEGRASS GROWN IN SOIL TREATED WITH VARYING RATES OF TRIPLE SUPERPHOSPHATE FERTILIZER IN THE GREENHOUSE

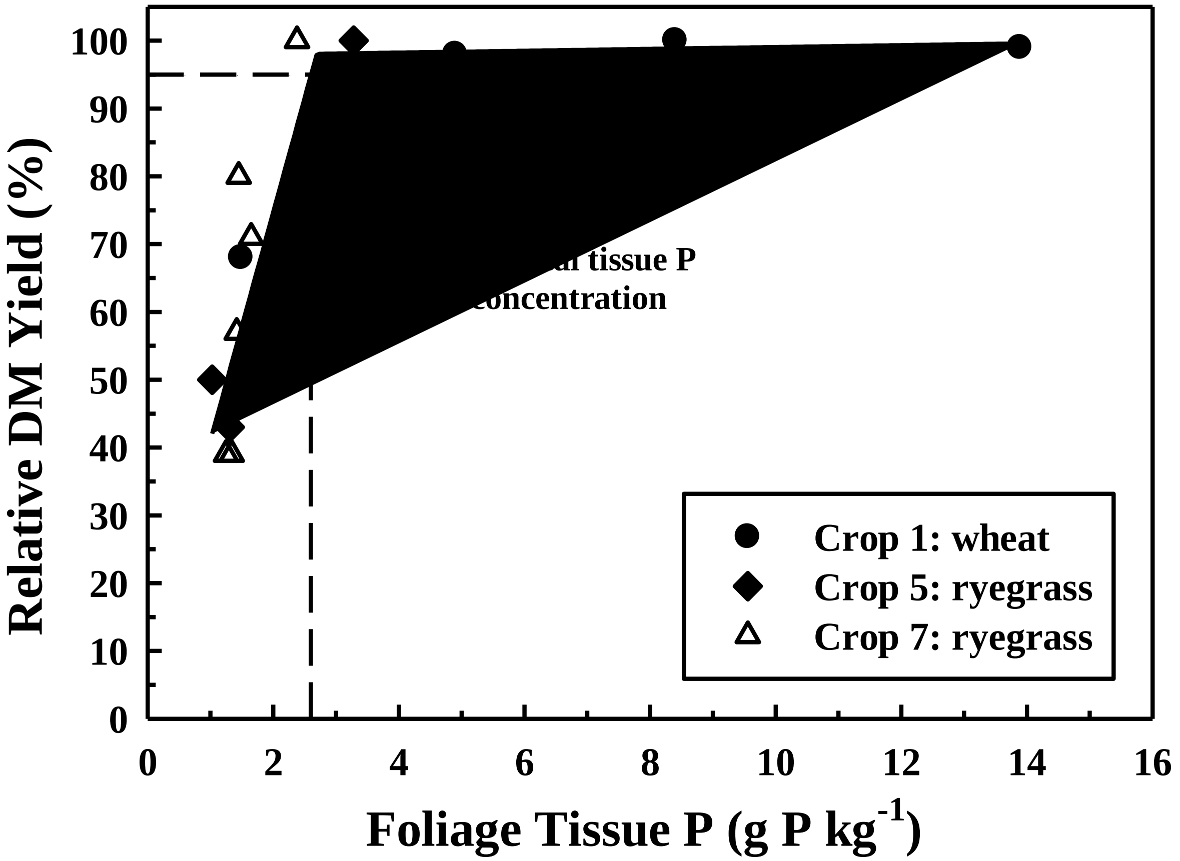


TABLE 1-4: FOLIAGE PHOSPHORUS CONCENTRATIONS AND SHORT-TERM BIOAVAILABLE PHOSPHORUS IN WHEAT GROWN IN SOIL AMENDED WITH THREE PHOSPHORUS SOURCES AT SIX TOTAL PHOSPHORUS RATES[1]

		Foliage P Concentration			Short term Bioavailable P
P Source	Actual P Rate	Crop 1	Crop 2	Crop 3	
	mg P kg^{-1} soil	--------------- g kg^{-1} tissue ---------------			mg pot^{-1}
Control	0	1.5 ± 0.21[2]	1.2 ± 0.41	1.7 ± 0.33	23 ± 6
AD	20	3.1 ± 0.87	2.0 ± 0.45	2.4 ± 0.31	59 ± 14
	38	4.9 ± 0.76	3.2 ± 0.45	3.0 ± 0.31	85 ± 8
	136	5.5 ± 1.08	5.8 ± 2.94	4.8 ± 0.59	116 ± 11
	190	5.4 ± 0.85	4.9 ± 2.53	4.5 ± 0.67	123 ± 27
	237	6.0 ± 0.70	4.5 ± 0.74	4.1 ± 0.44	121 ± 6
	350	7.0 ± 0.73	4.1 ± 0.47	4.2 ± 0.39	144 ± 13
CC	27	2.8 ± 0.73	2.3 ± 0.20	2.2 ± 0.37	57 ± 12
	47	3.0 ± 0.24	3.1 ± 0.21	2.7 ± 0.14	70 ± 5
	69	3.4 ± 0.49	3.0 ± 0.56	3.0 ± 0.34	78 ± 11
	160	3.1 ± 0.39	3.4 ± 0.53	3.3 ± 0.26	80 ± 12
	214	3.2 ± 0.43	3.3 ± 0.43	3.3 ± 0.19	85 ± 11
	268	3.8 ± 0.20	3.2 ± 0.24	3.3 ± 0.33	93 ± 8
TSP	27	4.9 ± 0.60	3.6 ± 0.57	2.8 ± 0.26	89 ± 11
	59	8.4 ± 1.01	8.8 ± 0.94	4.1 ± 0.54	173 ± 13
	85	13.9 ± 1.2	11.7 ± 1.30	5.0 ± 0.49	252 ± 8
	134	18.4 ± 0.7	15.1 ± 0.43	5.9 ± 0.18	281 ± 23
	185	20.8 ± 2.3	14.7 ± 1.95	5.1 ± 0.57	269 ± 27
	256	23.0 ± 3.3	16.6 ± 2.10	5.8 ± 0.37	294 ± 44

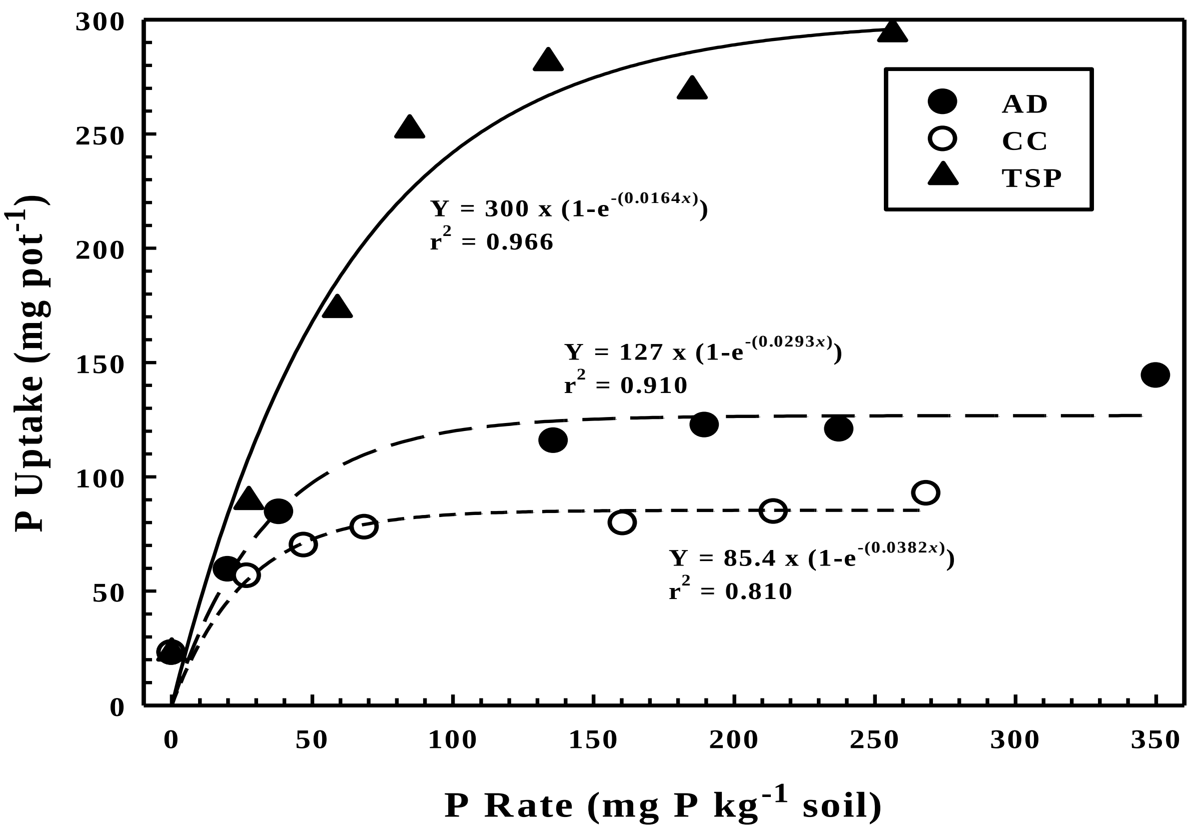
---

[1] Effect of all variables (P Source, P Rate, and P Rate x P Source) highly significant ($p<0.001$).

[2] Values are means ± standard deviation.

[3] Cumulative P uptake in first three crops of wheat.

FIGURE 1-4: SHORT-TERM PHOSPHORUS UPTAKE IN FOLIAGE OF THREE CONSECUTIVE 35-DAY CROPPING CYCLES WITH WHEAT IN SOIL TREATED WITH VARYING RATES OF AIR-DRIED AND CENTRIFUGE CAKE BIOSOLIDS AND TRIPLE SUPERPHOSPHATE FERTILIZER PHOSPHORUS IN THE GREENHOUSE



bioavailabilities of AD and CC biosolids which are 64 percent and 49 percent of TSP, respectively. In heavier textured soils with greater P binding capacity, the soil matrix controls the solubility and plant availability of applied P. Under this condition, the differences between fertilizer P and biosolids P on the bioavailability of applied P will be masked.

Long-Term Phosphorus Bioavailability. In this study, we defined long-term P bioavailability as the ability to maintain plant foliage P at a level that sustains optimum DM yield beyond short-term bioavailability. The long-term bioavailable P in each pot was estimated as the cumulative uptake for all crops up to and including the crop at which foliage P declined and remained below the critical level of 2.6 g P kg^{-1} upon further cropping. This represents the summation of the cumulative P uptake in the first three crops (short-term bioavailable P) and the subsequent additional P uptake until the soil became P-deficient. The foliage P concentrations in the final crop (Crop 18) ranged from 1.2 to 4.0 g P kg^{-1} (Table 1-5). Foliage P concentrations above the critical concentration in Crop 18 occurred at the three highest P application rates for biosolids and two highest application rates for TSP (Table 1-5). At those higher P rates where foliage P in Crop 18 was above the 2.6 g P kg^{-1} threshold, the cumulative P uptake for the entire study was considered long-term bioavailable P.

By the end of the study, in the treatments that were not P-deficient, the higher Bray-1 soil test P (up to 117 mg kg^{-1}; Table 1-3) and tissue P concentrations (up to 4.0 g kg^{-1}; Table 1-5) in the biosolids treatments were greater than in the TSP treatments. This indicates that the P remaining in the soil that might be bioavailable in the longer term (with further cropping beyond 18 crops) was greater in the biosolids than in the TSP treatments.

For all three P sources similar to the observation for short-term bioavailable P, the effect of P rate on long-term bioavailable P was greater for TSP than for the biosolids and was well described by an Exponential Rise to Maximum Two-Parameter model (Figure 1-5). Based on the model results, the maximum long-term potential P uptake for the P sources was 544, 460, and 332 mg P pot^{-1} for TSP and AD and CC biosolids, respectively. These results indicate that the relative long-term bioavailabilities of AD and CC biosolids are 85 percent and 61 percent of TSP, respectively, which are almost double the relative short-term bioavailabilities. The greater relative bioavailability in the long term compared to the short term is due primarily to the greater residual P uptake (the additional P uptake following the first three crops) in biosolids than in TSP (Table 1-4). McLaughlin and Champion (1987) have shown that with time, the relative fertilizer P efficiency of biosolids increased to that of monocalcium phosphate. These data are also consistent with other studies that show that the relative fertilizer P efficiency of biosolids increases with time (Miller and O'Connor, 2009; McLaughlin and Champion, 1987).

Conclusion

The data in this study show that the relative effectiveness of biosolids in increasing soil test P was about 78 percent relative to TSP for both biosolids. The effectiveness in increasing WSP was 15 percent for AD and 8 percent for CC biosolids. In sandy soils having low P-sorbing capacity, such as the Immokalee soil used in this study, P-binding to biosolids constituents

TABLE 1-5: CUMULATIVE LONG-TERM BIOAVAILABLE PHOSPHORUS UPTAKE IN FOLIAGE RESIDUAL UPTAKE AND FOLIAGE PHOSPHORUS CONCENTRATION IN CROP NO. 18 IN IMMOKALEE SAND AMENDED WITH THREE PHOSPHORUS SOURCES AT SIX TOTAL PHOSPHORUS RATES AND CROPPED WITH 18 CONSECUTIVE 35-DAY CROPPING CYCLES WITH WHEAT AND RYEGRASS ROTATION

P Source	Actual P Rate	Cumulative Long-term Phytoavailable P[1]	Residual P Uptake[2]	Foliage P in Crop 18[1]
	mg P kg^{-1} soil	---------------- mg pot^{-1}	--------	g kg^{-1}
Control	0	24 ± 5.3[3]		1.5 ± 0.27
AD	20	83 ± 31.5	24	1.4 ± 0.40
	38	162 ± 27.5	77	1.8 ± 0.72
	136	287 ± 21.8	171	2.3 ± 0.30
	190	353 ± 35	230	2.9 ± 0.24
	237	393 ± 18.4	272	3.7 ± 0.56
	350	450 ± 33.4	306	4.0 ± 0.23
CC	27	114 ± 37.3	57	1.6 ± 0.24
	47	158 ± 34.4	88	1.6 ± 0.39
	69	218 ± 12.4	140	2.1 ± 0.32
	160	293 ± 28.8	213	2.6 ± 0.21
	214	311 ± 11.5	226	2.9 ± 0.53
	268	335 ± 16.6	242	3.2 ± 0.12
TSP	27	130 ± 10.3	41	1.3 ± 0.27
	59	226 ± 20.3	53	1.2 ± 0.17
	85	342 ± 29.7	90	1.5 ± 0.35
	134	421 ± 28.8	140	2.2 ± 0.67
	185	446 ± 19.1	177	2.7 ± 0.74
	256	511 ± 46.4	217	3.8 ± 0.97

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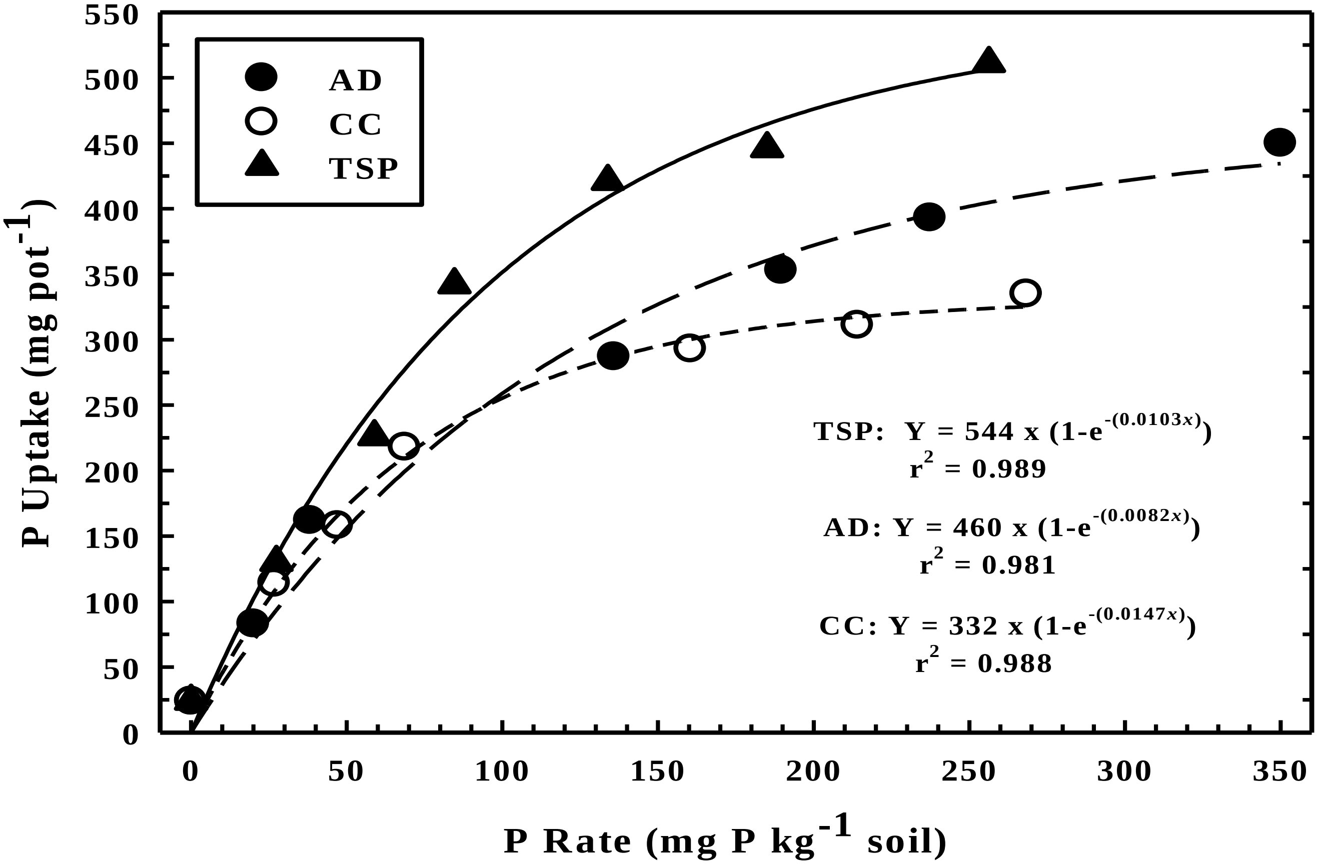
[1] Effect of all variables (P Source, P Rate, and P Rate x P Source) highly significant ($p<0.001$).
[2] Residual P uptake calculated as Long-term Bioavailable P minus Short-term Bioavailable P.
[3] Values are means ± standard deviation.

FIGURE 1-5: LONG-TERM PHOSPHORUS UPTAKE IN FOLIAGE DURING 18 CONSECUTIVE 35-DAY CROPPING CYCLES WITH WHEAT AND RYEGRASS ROTATION GROWN IN SOIL TREATED WITH VARYING RATES OF AIR-DRIED AND CENTRIFUGE CAKE BIOSOLIDS AND TRIPLE SUPERPHOSPHATE FERTILIZER PHOSPHORUS IN THE GREENHOUSE



controls the solubility and bioavailability of applied P. Therefore, the impact of applied P on soil test P and crop P uptake is less for biosolids than for chemical fertilizer P.

The bioavailability of biosolids P in the District's biosolids is in the range reported for other conventionally generated biosolids. At the P application rate associated with typical N-based application rates of District biosolids based on the maximum P uptake potential, the relative effectiveness of biosolids P in the short term is 43 and 28 percent for AD and CC biosolids, respectively. The relative effectiveness doubled in the long term. This indicates that in P-deficient soils, the bioavailability of biosolids P is lower than TSP, and the agronomic P rates for biosolids should be greater than for chemical P fertilizer.

CHAPTER 2

BIOAVAILABILITY OF BIOSOLIDS PHOSPHORUS – A FIELD STUDY[1]

Abstract

Information on plant availability of biosolids P is essential for developing P-based biosolids land-application guidelines, but information based on field studies is lacking. A field experiment was conducted from 2005 to 2008 at the District's Fulton County site. District lagoon-aged, air-dried biosolids were applied at a series of P rates (0, 75, 150, 225, 300 mg P kg^{-1} soil) along with commercial P fertilizer - TSP as reference. Biosolids and TSP were incorporated into surface soil (0 – 15 cm depth) once in late fall 2005. Corn (*Zea mays)* was planted for three consecutive years (2006 to 2008) and soil collected after each harvest in the fall and analyzed for WSP, Bray-1, and Mehlich-3 P. The concentrations of WSP and Bray-1 P following application of treatments were always lower in biosolids than TSP treatments at the same P rates for most of the observations over the three-year period, but Mehlich-3 P was similar for biosolids and TSP treatments. By the end of the study, P depletion was greater in TSP than in biosolids treatments. There was no significant effect of the P source or P rate on P uptake in corn grain or stover, but P concentrations in the corn tissues were greater in most TSP treatments than in biosolids treatments. The data show that biosolids P is less effective than TSP at increasing WSP and Bray-1 P in soil, and biosolids P is less bioavailable or prone to leaching losses. Higher rates of biosolids P are required to increase Bray-1 and WSP in soil, and thus, the applied P is less prone to leaching and runoff losses.

Objectives

The objectives of the study were to determine the bioavailability of P in biosolids, relative chemical fertilizer P, and the rate of depletion of soil extractable P and to validate these indices by measuring plant tissue P concentration and P uptake.

Materials and Methods

Study Site. The study was conducted during 2006 – 2008 at the District's site located at Fulton County in Western Illinois. The site has a continental climate with an annual mean air temperature of 10.4°C and annual precipitation of 1013 mm. The soil in the experimental plot was predominantly Clarksdale series (Fine smectitic, mesic Udollic Endoaqualf), with a small portion of Sable series (Fine-silty, mixed, superactive, mesic Typic Endoaquoll). Before the study, the field was cropped with corn for three years without P fertilization to deplete soil plant available P. At the establishment of treatment, soil extractable P values were 13.9 mg kg^{-1}(Bray-1 P) and 26.0 mg kg^{-1} (Mehlich-3 P). The surface soil had the following properties: pH 6.3, organic C 16.5 g kg^{-1}, total P 451 mg kg^{-1}, and silty clay loam texture (sand 123 g kg^{-1}, silt 617 g kg^{-1}, and clay 260 g kg^{-1}).

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[1] This study has been published in Tian, G., A. E. Cox, K. Kumar, T. C. Granato, G. A. O'Connor, and H. A. Elliott, "Assessment of Plant Availability and Environmental Risk of Biosolids – Phosphorus in a Midwest Corn-Belt Soil." *J. Environ Manag*. 172:171-176, 2016.

Treatment Design. The experimental design was a randomized complete block with four replications. The treatments included four biosolids rates, four TSP rates, and a control. The TSP treatments were included as reference. The typical N-based application rate for conventional biosolids produced at the District is 22.4 Mg ha^{-1} dry weight. We therefore designed the four biosolids rates as follows: 5.6 (0.25x), 11.2 (0.5x), 16.8 (0.75x) and 22.4 (1.0x) Mg ha^{-1}. Since the P concentration of the biosolids used in this study was 29.1 g P kg^{-1}, 650 kg P ha^{-1} was applied at the 1.0x N-based biosolids application, followed by 488, 325, and 163 kg P ha^{-1} for 0.75x, 0.5x and 0.25x N-based biosolids rates, respectively. The P rates for TSP treatments were the same as biosolids: 163, 325, 488, and 650 kg P ha^{-1}. No P was applied in the control. Based on a soil bulk density from 1.4 to 1.5 Mg m^{-3} in the 0-15 cm depth of experimental plots, the 163, 325, 488, and 650 kg P ha^{-1} of P rates were equivalent to loadings of 75, 150, 225, 300 mg P kg^{-1} soil. The P fertilizer requirement for 200-bushel corn in Illinois is typically 55 kg P ha^{-1} or 25 mg P kg^{-1} soil. Both P sources were applied only once in November 2005 for the three years of corn cropping (2006-2008). Large plots were used in this study with a treatment plot size of 0.1 ha (27 x 37 m).

Experimental Operation. The biosolids used in this study were the District's anaerobically digested lagoon-aged, air-dried biosolids. The analyses of biosolids are presented in Table 2-1. The biosolids were applied using a manure spreader and were incorporated into the plow layer by discing. Corn was planted in 2006, 2007, and 2008 and managed conventionally without irrigation. A blanket dose of 320 kg N ha^{-1} as urea and 110 kg K ha^{-1} as muriate of potassium, which could support the historically highest corn grain yield in the region, was broadcast each year at planting. Unfortunately, the 2006 corn crop was severely damaged by a hailstorm.

Sampling and Analysis. Soil samples (0 - 15 cm) were collected from each plot before the application of treatments in the fall of 2005 and in the fall of each crop harvest in 2006 – 2008. Soil samples at 15 – 30 cm depth were also collected at the beginning and end of the experiment. The soil samples were air-dried and ground to pass a 2-mm sieve. Samples of corn grain and stover were collected at harvest. The plant samples were oven-dried and ground to pass a 1-mm sieve.

The soil samples were analyzed for extractable P by water (1:10 soil:solution ratio; Self-Davis et al., 2000), Bray-1 (Bray and Kurtz, 1945) and Mehlich-3 (Mehlich, 1984) methods. The corn ear leaf, stover, and grain were analyzed for total P (USEPA, 1979).

Results

The Dynamics of Soil Extractable Phosphorus. Soil WSP in the biosolids treatments was lower compared to the TSP treatments and declined more slowly over time (Table 2-2). By fall 2008, the decline in WSP, as a percentage of 2006 levels, was lower in biosolids (13.4 to 40.6 percent) than in TSP (59.5 to 64.1 percent) treatments. At the end of three years of cropping, WSP values in biosolids treatments were still lower than those in TSP treatments for the same P rates, though the difference was not statistically different (Table 2-2). Soil WSP concentration responded

TABLE 2-1: ANALYSIS OF LAGOON-AGED, AIR-DRIED BIOSOLIDS USED IN THE STUDY

Analyte	Result (g kg^{-1})[1]
Volatile solids	394 ± 3
Organic N	14.4 ± 0.7
NO_3^--N	4.25 ± 0.24
NH_4^+-N	0.014 ± 0.01
Total Fe	30.9 ± 2.0
Oxalate extractable Fe	23.5 ± 0.1
Total Al	13.4 ± 1.1
Oxalate extractable Al	5.61 ± 0.01
Total Ca	51.9 ± 1.1
Total Mg	16.0 ± 0.5
Total P	29.1 ± 0.4
Extractable P	
Water	1.03 ± 0.01
Olsen	2.77 ± 0.08
Bray 1	14.5 ± 0.2
Mehlich 3	21.3 ± 0.5

[1] Mean ± SE, on a dry weight basis.

TABLE 2-2: EXTRACTABLE PHOSPHORUS IN 0 TO 15 cm DEPTH OF SOIL BEFORE – 2005 – AND AFTER – 2006, 2007, AND 2008 – BIOSOLIDS AND TRIPLE SUPERPHOSPHATE APPLICATION FOLLOWING CORN HARVEST[1]

P Source	P Rate	2005	2006	2007	2008	Decline in Extractable P[2]
		------------------------------- WSP ($mg\ kg^{-1}$ soil)			-----------------------	-------- % ------
Control	0	2.0 ± 1.2	2.2 ± 1.2	1.6 ± 0.8	1.3 ± 0.9	39.7
Biosolids	75	1.2 ± 0.3	2.4 ± 0.8	1.6 ± 0.7	1.9 ± 0.9	19.8
	150	1.8 ± 1.3	5.2 ± 1.4	3.7 ± 0.8	3.1 ± 1.3	40.6
	225	1.9 ± 1.1	7.5 ± 1.6	7.1 ± 2.4	6.1 ± 2.3	18.7
	300	1.2 ± 0.4	6.5 ± 1.6	5.4 ± 2.8	5.7 ± 2.7	13.4
TSP	75	1.3 ± 0.5	5.6 ± 2.6	3.8 ± 1.1	2.0 ± 1.0	63.3
	150	1.8 ± 0.6	13.8 ± 4.1	8.0 ± 3.1	5.5 ± 1.5	60.3
	225	2.1 ± 0.5	19.8 ± 4.4	12.7 ± 2.6	8.0 ± 3.2	59.5
	300	1.3 ± 0.3	21.9 ± 4.9	14.0 ± 2.5	7.9 ± 1.1	64.1
		-------------------------- Bray-1 P ($mg\ kg^{-1}$ soil)			-----------------------	-------- % -----
Control	0	16.8 ± 7.4	18.0 ± 9.6	17.6 ± 8.7	13.7 ± 8.1	23.8
Biosolids	75	11.4 ± 5.2	23.4 ± 7.9	22.7 ± 7.1	23.2 ± 14.0	0.7
	150	14.1 ± 8.7	35.7 ± 7.3	46.3 ± 13.9	32.9 ± 11.6	7.6
	225	12.7 ± 4.9	51.7 ± 7.2	75.4 ± 23.9	58.2 ± 8.9	-12.6
	300	11.5 ± 3.2	58.7 ± 14.2	70.5 ± 23.6	60.3 ± 12.3	-2.7
TSP	75	12.8 ± 6.3	32.6 ± 12.3	31.4 ± 9.5	21.5 ± 8.9	34.1
	150	16.9 ± 1.5	60.4 ± 11.9	55.1 ± 13.1	43.8 ± 9.2	27.4
	225	15.8 ± 3.4	79.3 ± 16.0	82.2 ± 11.6	56.6 ± 15.6	28.6
	300	12.0 ± 4.6	101.7 ± 12.0	81.8 ± 11.6	52.2 ± 5.8	48.7
		-------------------- Mehlich-3 P ($mg\ kg^{-1}$ soil)			----------------------	------- % ------
Control	0	28.3 ± 13.4	26.4 ± 15.0	24.2 ± 12.7	20.5 ± 12.1	22.2
Biosolids	75	22.4 ± 11.0	47.5 ± 22.0	36.5 ± 12.4	39.6 ± 30.2	16.5
	150	26.9 ± 14.2	91.4 ± 20.8	87.2 ± 25.5	63.3 ± 22.6	30.7
	225	23.9 ± 10.9	134.4 ± 17.9	139.6 ± 47.8	104.7 ± 18.6	22.1
	300	21.4 ± 8.8	155.1 ± 43.0	134.1 ± 37.3	120.6 ± 34.3	22.2

TABLE 2-2 (Continued): EXTRACTABLE PHOSPHORUS IN 0 TO 15 cm DEPTH OF SOIL BEFORE – 2005 - AND AFTER - 2006, 2007, AND 2008 - BIOSOLIDS AND TRIPLE SUPERPHOSPHATE APPLICATION FOLLOWING CORN HARVEST[1]

P Source	P Rate	2005	2006	2007	2008	Decline in Extractable P[2]
		------------------------------------- Mehlich-3 P (mg kg^{-1} soil) -------------------------------------				
TSP	75	23.8 ± 13.1	50.9 ± 20.1	48.0 ± 15.7	35.3 ± 15.6	30.6
	150	31.9 ± 7.2	97.1 ± 21.9	81.8 ± 17.6	68.1 ± 11.9	29.9
	225	30.5 ± 10.7	128.4 ± 28.7	111.9 ± 17.81	88.7 ± 26.8	30.9
	300	21.4 ± 7.3	152.5 ± 37.6	116.8 ± 15.2	83.5 ± 9.3	45.3

[1] Biosolids and TSP treatments were applied in fall 2005. Values are means ± standard deviation.

[2] Decline in extractable P calculated as the difference between levels in 2006 and 2008 and expressed as a percentage of levels in 2006.

to the P rates differently in biosolids P and TSP treatments (Figure 2-1a). Based on the slope of linear response to the P rate (0.018 for biosolids and 0.072 for TSP), the effectiveness of biosolids P measured following the first corn crop (2006) in increasing WSP was only 25 percent of TSP (Figure 2-1a). By the end of the study, the differences in response of WSP to the P rate for biosolids and TSP was not statistically significant (Figure 2-1b).

Bray-1 P, before the application of treatments and in the control throughout the study (Table 2-2), was well below the soil test P sufficiency level of 30 mg P kg^{-1} for corn on high P-supplying soil in Illinois (IL Agronomy Handbook, 2009). Bray-1 P in fall 2006 was lower in biosolids than in TSP treatments at the corresponding P rates (Table 2-2). Soil Bray-1 P declined with cropping in TSP but not in the biosolids treatments, leading to the convergence of the soil Bray-1 P concentrations for two P sources three years after the P application. By fall 2008, there was essentially no change in Bray-1 P, compared to 2006 levels, in biosolids treatments, but the decline in TSP was 27.4 to 48.7 percent relative to 2006 (Table 2-2). The response to the P rate in 2006 was linear. Based on the slope of linear response to P rate (0.146 for biosolids and 0.285 for TSP), the effectiveness of biosolids P relative to TSP in increasing Bray-1 P was 50 percent (Figure 2-2a). At the end of the study (2008), the effect of the P application rate on Bray-1 P was similar for both biosolids and TSP (Figure 2-2b).

At each P rate, the increase in soil Mehlich-3 P was the same for biosolids and TSP (Table 2-2), and the response for both was linear ($Y = 22.4 + 0.455x$, $r = 0.991$). With time, soil Mehlich-3 P declined in all treatments more slowly in the biosolids than in the TSP treatments. By fall 2008, the decline in Mehlich-3 P, as a percentage of 2006 levels, was lower in biosolids (16.5 to 30.7 percent) than in TSP (29.9 to 45.3 percent) treatments.

At the first soil sampling following application of biosolids and TSP treatments (fall 2006), Bray-1 P in the 0 – 15 cm soil depth was well correlated with WSP (WSP = 0.254 x Bray-1 P – 3.61; r = 0.947). However, the correlation between Bray-1 and Mehlich-3 P was different for TSP (Mehlich-3 P = 1.54 x Bray-1 P +1.16; r = 0.999) and biosolids (Mehlich-3 P = 3.15 x Bray-1 P – 25.16; r = 0.999).

There were no differences between the treatments in any of all three extractable P indices in the 15 – 30 cm depth at the end of the study (data not shown).

Phosphorus Concentration and Uptake in Corn Tissues. In all years, P addition increased stover P concentrations for both P sources; however, at most P rates, it was lower in biosolids than in TSP treatments, particularly for the first two years (Figure 2-3a). The response of grain P concentration to P addition was less pronounced. However, for some P rates during the three years of cropping, the grain P concentration was still lower in biosolids than in TSP treatments (Figure 2-3b).

The corn DM yield and P uptake during the three years are presented in Table 2-3. Corn grain yields in 2006 were only about one-half those in 2007 and 2008 due to severe hail damage. There was no effect of the P rate on DM yield or on P uptake. Although not statistically significant, total P uptake in grain and stover at most P rates tended to be higher in TSP than in biosolids treatments. Based on 2007 and 2008 data, the mean annual P uptake in grain for biosolids and TSP treatments was 30.2 and 31.1 kg P ha^{-1} (~13.5 and 13.8 mg P kg^{-1} soil), respectively.

FIGURE 2-1: EFFECT OF PHOSPHORUS RATE ON WATER-SOLUBLE PHOSPHORUS IN THE 0 - 15 cm SOIL DEPTH AFTER CORN CROP IN FALL 2006 AND 2008 IN PLOTS AMENDED WITH BIOSOLIDS AND TRIPLE SUPERPHOSPHATE IN FALL 2005

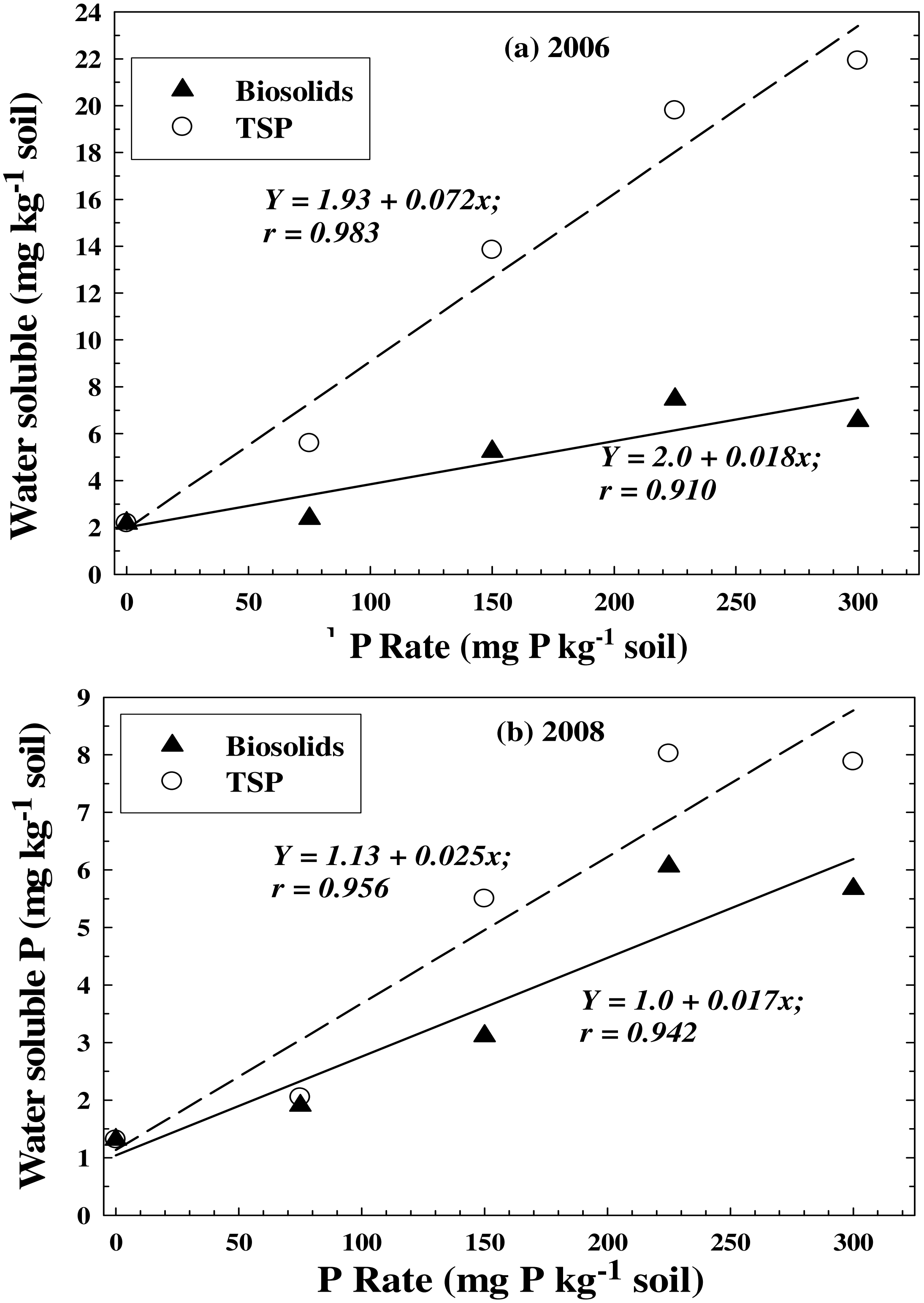


FIGURE 2-2: EFFECT OF PHOSPHORUS RATE ON BRAY-1 PHOSPHORUS IN THE 0 - 15 cm SOIL DEPTH AFTER CORN CROP IN FALL 2006 AND 2008 IN PLOTS AMENDED WITH BIOSOLIDS AND TRIPLE SUPERPHOSPHATE IN FALL 2005

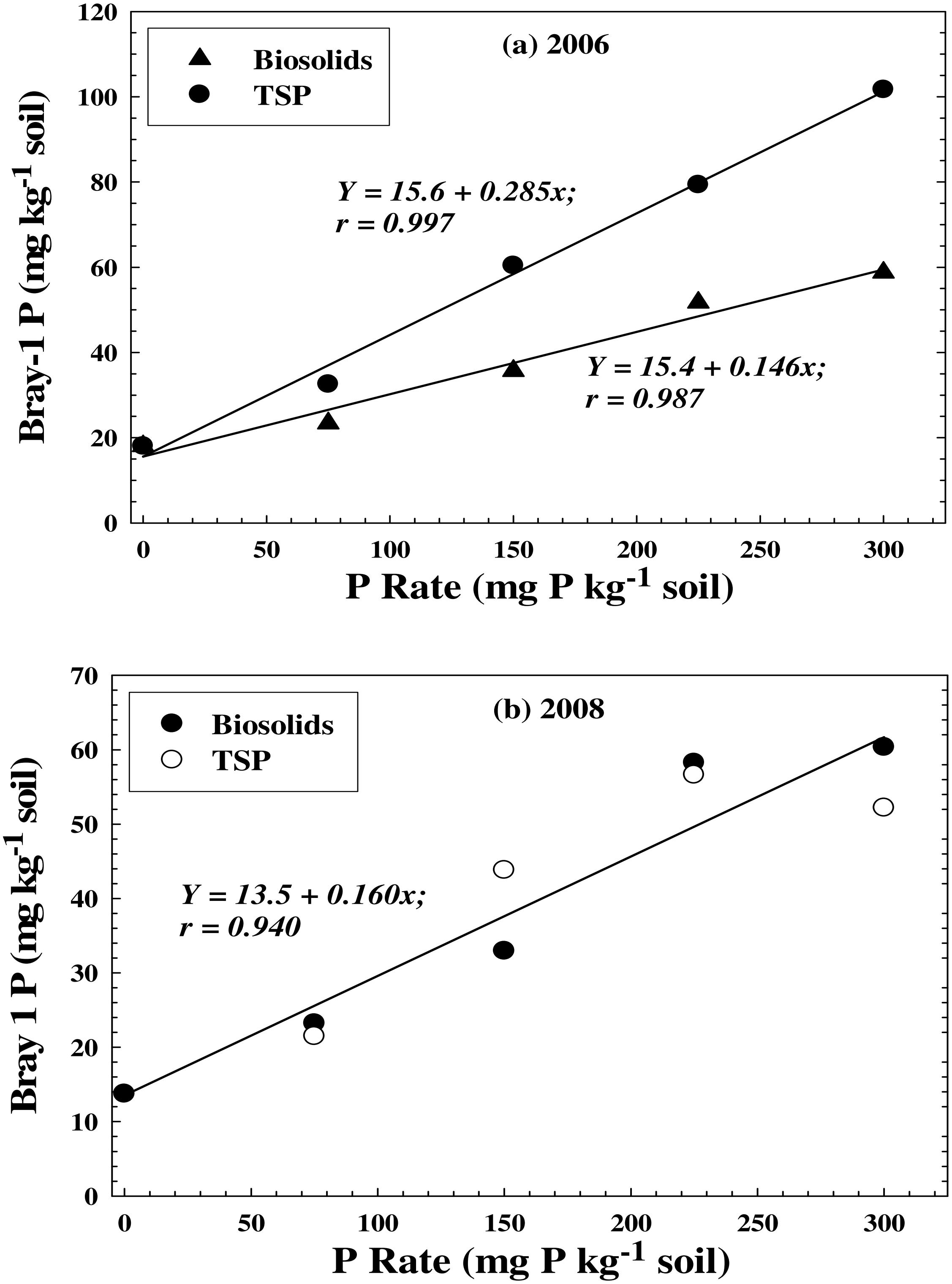


FIGURE 2-3: RESPONSE OF PHOSPHORUS CONCENTRATION IN CORN STOVER AND GRAIN TO THE PHOSPHORUS RATES APPLIED AS TRIPLE SUPERPHOSPHATE AND BIOSOLIDS DURING THE THREE YEARS OF CROPPING CYCLES. BARS REPRESENT STANDARD ERROR

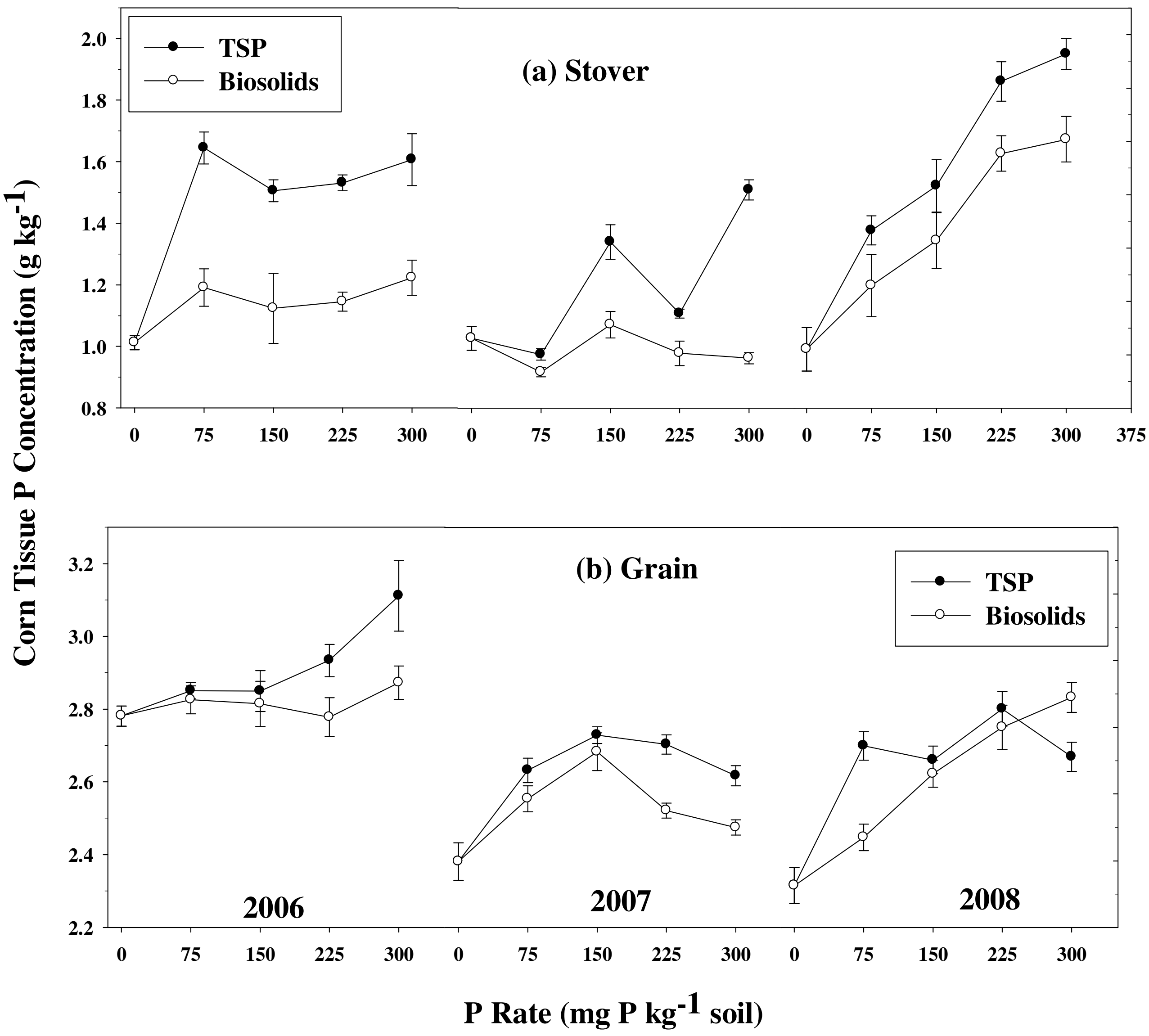


TABLE 2-3: MEAN CORN GRAIN AND STOVER BIOMASS YIELD AND PHOSPHORUS UPTAKE DURING THE THREE YEARS OF CORN CROP PRODUCTION ON SOIL AMENDED WITH FOUR RATES OF BIOSOLIDS AND TRIPLE SUPERPHOSPHATE FERTILIZER

			Biomass (Mg ha^{-1})		P Uptake (kg ha^{-1})		
Year	P Source	P Rate	Grain	Stover	Grain	Stover	Total
2006	Control	0	5.79	7.01	14.9	6.5	21.4
	Biosolids	75	6.48	7.46	16.9	8.2	25.1
		150	7.04	8.14	18.3	8.4	26.7
		225	6.87	8.30	17.6	8.8	26.4
		300	6.26	8.11	16.6	9.2	25.7
	TSP	75	5.16	6.99	13.6	10.6	24.2
		150	6.31	8.54	16.6	11.9	28.4
		225	6.79	7.88	18.4	11.1	29.5
		300	4.79	7.12	13.7	10.5	24.3
2007	Control	0	11.76	8.43	26.0	5.4	31.4
	Biosolids	75	11.67	7.24	27.8	3.7	31.5
		150	12.08	8.41	30.4	5.9	36.2
		225	12.11	9.34	28.5	5.5	33.9
		300	11.63	9.01	26.8	5.1	31.9
	TSP	75	11.76	7.84	29.0	4.5	33.5
		150	11.13	8.22	28.5	8.4	36.9
		225	11.55	9.06	29.3	6.7	36.0
		300	10.99	8.59	26.9	10.5	37.4
2008	Control	0	12.35	12.42	26.5	9.4	35.9
	Biosolids	75	13.08	12.67	29.8	12.4	42.2
		150	13.21	12.04	32.4	13.6	46.1
		225	13.43	12.89	34.7	18.5	53.2
		300	14.50	13.97	38.6	20.7	59.4
	TSP	75	12.91	13.90	32.7	16.2	48.9
		150	12.66	13.07	31.6	17.3	48.8
		225	12.17	12.45	32.1	21.0	53.0
		300	12.57	14.09	31.4	25.1	56.5

TABLE 2-3 (Continued): MEAN CORN GRAIN AND STOVER BIOMASS YIELD AND PHOSPHORUS UPTAKE DURING THE THREE YEARS OF CORN CROP PRODUCTION ON SOIL AMENDED WITH FOUR RATES OF BIOSOLIDS AND TRIPLE SUPERPHOSPHATE FERTILIZER

			Biomass (Mg ha^{-1})		P Uptake (kg ha^{-1})		
Year	P Source	P Rate	Grain	Stover	Grain	Stover	Total
Cumulative	Control	0	29.90	27.86	67.4	21.4	88.7
	Biosolids	75	31.23	27.37	78.6	29.0	107.6
		150	32.33	28.60	78.4	34.1	112.5
		225	32.40	30.52	79.0	36.4	115.4
		300	32.39	31.09	74.9	44.7	119.7
	TSP	75	29.84	28.73	75.2	31.4	106.6
		150	30.10	29.82	76.7	37.5	114.2
		225	30.52	29.39	79.8	38.8	118.5
		300	28.35	29.80	72.1	46.1	118.2

Discussion

Among the three soil extractable P indices, WSP and Bray-1 P showed that biosolids are less effective than TSP in increasing soil extractable P. The Mehlich-3 method showed that biosolids are not different from TSP in increasing soil extractable P. About 30 percent of P in biosolids is in Ca-bound minerals, which have extremely low solubility. Since Mehlich-3 is a stronger extractant than Bray-1 or water, it was probably more effective in the extraction of Ca-bound P associated with the biosolids, leading to the higher extractable P in biosolids-amended soil. The greater effectiveness of Mehlich-3 is also shown in the extractable P concentrations in the biosolids used in this study (Table 2-1). Extractable P in the biosolids as a percentage of total P was 50 and 73 percent for Bray-1 and Mehlich-3, respectively. Sharpley et al. (2004) and Reiter et al. (2013) have also reported the greater effectiveness of the Mehlich-3 extractant. By the end of the three years, biosolids-P became more equilibrated with soil, lowering the dominance of biosolids components on the chemistry and extractability of applied P. This resulted in a similar P rate effect on Bray-1 P (Figure 2-2) and, to some extent, on WSP (Figure 2-1) for biosolids and TSP.

Crop P uptake (Table 2-3) was not correlated with changes in soil extractable P. However, the decrease in extractable P levels during the three years, as measured by all three indices, was greater in TSP than in the biosolids treatment. This indicates that biosolids P is less prone to crop uptake and leaching in the short term and, therefore, will be available over a longer period of time. Barbarick and Ippolito (2003) reported that AB-DTPA soil extractable P concentration in the 0 – 20 cm depth decreased to levels in the control with three croppings after termination of five excessive biosolids applications in Colorado.

The P concentrations in corn tissue in this study showed the lower availability of P in biosolids as fertilizer than the commercial fertilizer. The data from this study confirm that the P in biosolids can be a stable P source and it can be applied at a higher rate than TSP for increasing soil test P. Shober and Sims (2003) emphasized that some properties of biosolids can mitigate the environmental risk of biosolids P to water quality. Such unique properties are due to Fe and Al oxides in biosolids (McCoy et al., 1986; Elliott et al., 2002). As shown in Table 2-1, biosolids is relatively high in Fe and Al, and most are in the oxalate-extractable form. Oxalate extractable Fe and Al represent Fe and Al oxides in non-crystalline, colloidal amorphous form with large specific surface area (Karltun et al., 2000) and large numbers of valence-unsatisfied hydroxyl groups (McBride, 2000). Being different from crystalline iron oxides, such as goethite, the amorphous complex of Fe and Al oxides can effectively adsorb/bind the phosphate (Nanzyo, 1986), increasing the P stability in soil.

Conclusion

The three-year field study demonstrated that P in the District's conventionally treated biosolids is considerably less effective than commercial P fertilizer in increasing soil extractable P and corn tissue P concentrations. The P in biosolids can be regarded as a stable P source with lower potential for plant uptake and losses of soluble P from fields through leaching and runoff. The lower potential for crop uptake and losses leads to slower depletion of applied biosolids over time. However, the impact of applied biosolids P on soil P status and bioavailability will depend on soil type, initial P levels, and biosolids characteristics that affect the chemistry of biosolids P.

CHAPTER 3

POTENTIAL FOR PHOSPHORUS LOSSES IN SURFACE RUNOFF FROM SOIL AMENDED WITH REPEATED AND LONG-TERM BIOSOLIDS APPLICATIONS

Abstract

These studies involved quantification of runoff P losses from soils that have received biosolids application from no application to as high as 1,073 Mg ha^{-1} cumulative application during the 33 years of reclamation. The objective was to estimate the potential for P losses in biosolids amended soils and the biosolids P loading required to increase soil test P to the critical environmental impact threshold above which the potential for runoff P losses from agricultural fields increases significantly. Results showed that soil test P (Bray-1 P, Mehlich-3 P, and Oxalate-P, and WSP) increased with cumulative biosolids loadings. The changes in soil test P (Bray-1 P, Mehlich-3 P or WSP) were highly correlated with the cumulative biosolids application. However, the increases in soil test P were not linear. Soil test P increased exponentially with cumulative biosolids loadings, approaching a maximum at the highest biosolids cumulative loading. Biosolids contain appreciable amounts of Fe and Al, and application of biosolids significantly increased the soil oxalate-extractable Fe and Al. The oxalate-extractable Fe and Al are amorphous forms of Fe and Al oxides and relatively reactive due to their high surface area and thus may adsorb P very strongly. Oxalate-extractable P, Fe, and in soil Al were used to calculate PSI, which then was related to the risk of P transport or losses from different soils. The PSI and WSP data from the long-term biosolids application fields were well described by a Piecewise-2-Segment Linear model, which showed the critical change point at PSI = 37 and WSP = 10 mg P kg^{-1}. Above this PSI, the response of WSP increased significantly, eventually reaching the range observed for pure biosolids. In the second part of this study, the relationship between runoff P, WSP, and PSI from the simulated runoff study was evaluated by regression analysis. The results showed that the model fitted very well with the coefficient of determination values of 0.93 for PSI vs. WSP and 0.94 for PSI vs. runoff DMRP. The critical change point above which there was a sharp increase in WSP or runoff DMRP losses was a PSI of 37 and 40, respectively, which were similar to those estimated from a previous laboratory experiment (PSI 31) relating PSI with WSP. Thus, for long-term biosolids application fields, the critical P saturation was between 30 to 40 percent based on oxalate extractable P, Al, and Fe; above this saturation point, there may be a greater risk of P losses to the water either via leaching to groundwater or via runoff to surface waters. The critical change point PSI values of 31 from the laboratory experiment and 37 and 40 from the runoff simulation experiment corresponded to cumulative biosolids loading of 130 – 160 Mg ha^{-1}. Thus, the results from this study show that repeated and long-term biosolids application up to a cumulative loading of 160 Mg ha^{-1} is safe with no significant risk of runoff P losses from the fields if agronomic best management practices are followed.

Objective

The objective of this study was to estimate the potential for P losses in biosolids amended soil and the biosolids P loading required to increase soil test P to the critical environmental impact threshold above which the potential for runoff P losses from agricultural fields increases significantly.

Materials and Methods

The study included two separate experiments: a laboratory experiment and a simulated runoff experiment.

Laboratory Experiment. The 0- to 15-cm depths of soils from 13 fields located at the Fulton County site sampled at various years were selected for the study to represent a wide range in cumulative P loading. Two of these fields did not receive biosolids (unamended), and the other 11 fields received biosolids (amended), with the last applications being made 13 to 25 years before samples were collected for this study. The biosolids applied to these fields were generated at the District's Stickney and Calumet Water Reclamation Plants (WRP). Details on types of biosolids, methods of application, and crop management on these fields are presented in detail in Tian et al. (2009). The predominant textures of the soils in these fields are silt loam and silty clay loam. The list of fields and their biosolids application history are presented in Table 3-1. Most of the fields selected consist of in-place soil (non-mined) that has not been impacted by mining operations. At three of the 13 fields, there are separate areas of mine-spoil and non-mined soil. We included both areas of those three fields, resulting in a total of 16 fields sampled. We included Field 75, which consists entirely of mine-spoil, because the cumulative amount of biosolids applied to this field is quite different from the other fields, and this would increase the variability within the range of soil P levels we evaluated.

A total of 45 soil samples were used in the laboratory experiment. This included samples that were collected in 2004 and some of the archived samples that were collected from the fields annually since biosolids application began in those fields. The number of samples that were selected from each field area is shown in Table 3-1. The soil samples were air-dried and then screened through a 2-mm sieve.

The 45 soil samples were analyzed for soil pH (1:2, soil:water), total P using microwave-assisted digestion in nitric acid (USEPA 3052 method), oxalate-extractable P, Al, and Fe – 0.2 M ammonium oxalate (pH 3), 1:40 soil:solution ratio, two-hour extraction in the dark, soil test P: Bray-1 and Mehlich-3 - 1:7.5 and 1:10 soil:solution ratio, respectively; and WSP:1:25 soil:water ratio, one-hour shaking.

Simulated Runoff Experiment. For the runoff experiment, 11 bulk soil samples from a total of nine field areas (includes mine-spoil and non-mined) were used (Table 3-1). The fields were selected to obtain a wide range in cumulative P loadings. About 50 kg of each of the 11 soils were collected, air-dried, and then screened through a 2-mm sieve. The runoff simulation was set up and conducted according to the NPRP protocol (NPRP, 2006). The experiment was set up as a completely randomized block design, consisting of 11 soils and 4 replications using specially constructed trays. Soil trays were constructed from galvanized sheet metal according to the approach used in the NPRP protocol. The inside dimensions of the trays were 100-cm long x 20-cm wide x 7.5-cm high (the down-slope side of the tray will be only 5-cm high). At the down-slope end of the tray, a V-shaped trough was attached to collect runoff.

TABLE 3-1: CHARACTERISTICS AND CUMULATIVE BIOSOLIDS LOADING FOR SOIL SAMPLES COLLECTED FROM FIELDS WHERE BIOSOLIDS WERE APPLIED TO STRIP-MINED AND NON-MINED FIELDS AT THE FULTON COUNTY SITE

Field No.	Soil Taxonomy	Type of Land	Sample Year	Cumulative Biosolids Applied	pH	Bray-1 P	OC	CEC	Tot-Fe	Tot-Al
				Mg ha^{-1}		mg kg^{-1}	%	meq 100 g^{-1}	mg kg^{-1}	mg kg^{-1}
10	Keomah silt loam: Fine, smectitic, mesic, Aeric Endoaqualfs	NM	1974	0	6.05	27.5	0.47	15.9	429	914
		NM	1977	170	6.65	28.3	2.45	19.1	1,118	854
		NM	1979	300	6.03	ND	3.95	28.0	2,934	1,456
		NM	2004	1073	6.30	ND	4.91	ND	ND	ND
19	Clarksdale silt loam: Fine smectitic, mesic Udollic Endoaqualfs	NM	1972	0	5.95	51.6	2.88	18.2	255	497
		NM	1979	263	5.77	402.8	3.15	23.7	2,814	1,124
		NM	1982	530	ND	ND	3.82	ND	ND	ND
		NM	2004	641	6.60	ND	3.13	ND	ND	ND
20	Ipava silt loam: Fine, smectitic, mesic Aquic Argiudolls	NM	1972	0	6.25	45.5	1.89	25.6	196	682
		NM	1976	74	5.30	82.6	2.03	28.1	725	1,589
		NM	1981	325	6.26	267.3	4.62	43.8	2,439	1,654
		NM	2004	530	6.70	ND	3.92	ND	ND	ND
21	Greenbush silt loam: Fine-silty, mixed, superactive, mesic Mollic Hapludalfs	NM	1972	0	6.70	50.7	1.35	18.1	209	596
		NM	1975	64	5.90	40.5	1.35	16.8	481	625
		NM	1982	426	ND	ND	4.30	ND	ND	ND
		NM	2004	614	6.60	ND	3.27	ND	ND	ND
22	Clarksdale silt loam: Fine smectitic, mesic Udollic Endoaqualfs	NM	1972	0	7.15	41.3	1.19	22.3	172	555
		NM	1977	97	5.65	222.3	1.96	21.9	987	1,510
		NM	1980	236	6.14	327.3	4.20	33.5	2,982	1,436
		NM	2004	448	6.60	ND	3.18	ND	ND	ND

TABLE 3-1 (Continued): CHARACTERISTICS AND CUMULATIVE BIOSOLIDS LOADING FOR SOIL SAMPLES COLLECTED FROM FIELDS WHERE BIOSOLIDS WERE APPLIED TO STRIP-MINED AND NON-MINED FIELDS AT THE FULTON COUNTY SITE

Field No.	Soil Taxonomy	Type of Land	Sample Year	Cumulative Biosolids Applied	pH	Bray-1 P	OC	CEC	T-Fe	T-Al
				Mg ha^{-1}		mg kg^{-1}	%	meq 100 g^{-1}	mg kg^{-1}	mg kg^{-1}
23	Clarksdale silt loam: Fine smectitic, mesic Udollic Endoaqualfs	NM	1974	0	6.40	28.3	1.06	20.0	173	514
		NM	1977	56	6.40	119.8	1.06	20.4	732	1,183
		NM	1979	166	6.20	351.5	3.12	31.8	2,558	1,220
		NM	2004	473	6.50	ND	3.02	ND	ND	ND
31	Orthents, silty, undulating: Coarse-silty, mixed, superactive, nonacid, mesic Aquic Udifluvents	NM	1974	0	5.30	18.4	0.48	20.6	218	478
		NM	1979	255	5.95	ND	2.84	29.9	2,884	1,172
		NM	1981	389	6.00	274.3	3.59	34.8	3,424	1,901
		NM	2004	557	6.60	ND	2.54	ND	ND	ND
34	Clarksdale silt loam: Fine smectitic, mesic Udollic Endoaqualfs	NM	1975	0	6.85	5.4	0.17	16.6	46	338
		NM	1978	153	6.56	352.0	2.51	22.5	1,658	1,140
		NM	1980	271	6.31	304.3	2.97	28.7	2,102	1,258
		NM	2004	566	6.80	ND	2.68	ND	ND	ND
40	(1/2) Rapatee silty clay loam: Fine-silty, mixed, supaeractive, nonacid, mesic Alfic Udarents, (1/2) Sable silty clay loam: Fine-silty, mixed, mesic Typic Endoaqualfs	MS + NM	1975	0	7.40	23.0	1.50	23.4	218	809
		MS + NM	1978	84	5.75	316.3	2.53	31.1	1210	1,465
		MS + NM	1981	272	6.45	314.3	3.85	30.1	2,337	1,857
		MS + NM	2004	497	6.80	ND	3.81	ND	ND	ND
		MS + NM	2004	497	ND	ND	ND	ND	ND	ND

TABLE 3-1 (Continued): CHARACTERISTICS AND CUMULATIVE BIOSOLIDS LOADING FOR SOIL SAMPLES COLLECTED FROM FIELDS WHERE BIOSOLIDS WERE APPLIED TO STRIP-MINED AND NON-MINED FIELDS AT THE FULTON COUNTY SITE

Field No.	Soil Taxonomy	Type of Land	Sample Year	Cumulative Biosolids Applied	pH	Bray-1 P	OC	CEC	Tot-Fe	Tot-Al
				Mg ha^{-1}		mg kg^{-1}	%	meq 100 g^{-1}	mg kg^{-1}	mg kg^{-1}
51	Lenzburg silt loam: fine-loamy, mixed, active, calcareous, mesic Alfic Udarents and Keomah Silt loam:Fine, smectitic mesic, Aerie Endoaqualfs	MS + NM	1987	0	ND	ND	1.13	ND	23,221	12,613
		MS + NM	2004	42	7.40	ND	1.44	ND	ND	ND
		MS + NM	2004	42	ND	ND	ND	ND	ND	ND
59	Clarksdale silt loam: Fine mectitic, mesic Udollic Endoaqualfs	NM	2004	0	6.70	ND	1.31	ND	ND	ND
75	Lenzburg silt loam: Fine-loamy, mixed, active, calcareous, mesic Alfic Udarents	MS	1979	0	8.02	16.4	0.33	17.4	529	555
		MS	2004	334	7.40	ND	1.10	ND	ND	ND
83	(1/2) Clarksdale silt loam: Fine smeectitic, mesic Udollic Endoaqualfs and (1/2) Sable silty clay loam: Fine-silty, mixed superactive, mesic Typic Endoaqualfls	NM	2004	0	6.90	ND	2.08	ND	ND	ND

ND – Not determined

A metal frame was constructed to support up to eight of the soil trays at approximately 45-cm above the ground. The frame was designed such that the trays can be tilted at various angles to simulate different slopes.

The bottom of the trays was lined with cheesecloth, and then the amount of soil required to fill the trays to 5-cm deep at ~1.5 Mg m^{-3} bulk density were packed with the aid of a wooden damper. Water was to be added slowly to the soil in the trays until they were saturated. The saturated trays were covered with plastic to minimize moisture loss and left to equilibrate for one day before simulated rainfall was applied to the soil.

Rainfall Simulator Set-Up and Calibration. The rainfall simulator was set up on the ground of the laboratory at the Fulton County site to have ready access to electricity and RO water. The RO water supply was at approximately pH 6.7, and the total P content was less than 0.01 mg P L^{-1}. The rainfall simulator (Joern's Inc., West Lafayette, IN) was similar to that described for the NPRP studies. The simulator consists of piping, an electrical pump, a pressure gauge, and a TeeJet 1/2 HH SS 50 WSQ nozzle (Spraying Systems Co, Wheaton, IL) mounted on an aluminum frame (2.3-m wide x 2.8-m long x 3-m high) and covered with a plastic tarp to provide a windscreen. A polypropylene tank was used as a reservoir to contain enough water for each simulated rainfall event.

The flow meter was calibrated to deliver water at a rate equivalent to 7.0 cm hr^{-1} (specified in the NPRP protocol) over the area covered by the spray nozzle. The uniformity of the rainfall delivered to the trays was recorded by running the simulator and measuring the depth of water collected in containers placed at multiple locations within the 2 x 2-m area under the nozzle. The uniformity of the rainfall intensity was calculated as:

Coefficient of Uniformity (CU) = 1 – (standard deviation/mean).

The results of the calibration showed that delivery of the simulated rainfall was uniform (CU > 0.8).

Simulated Rainfall Procedure. The rainfall simulations were done according to the NPRP approach. The packed trays were randomly placed on the metal frame (45-cm above the ground level) at an angle equivalent to a 4-percent slope. A series of three runoff events was conducted on each set of trays for a 30-minute duration at a rate of 7.0 cm hr^{-1}. The second and third events were conducted at three and seven days after the first event, respectively. Pre-weighed 4.5-L plastic bottles and funnels were placed under the collection trough at the down-slope end of the trays to collect the runoff generated during each 30-minute period.

The runoff in the bottles was stirred thoroughly. An aliquot of approximately 100 mL was filtered through a 0.45-µm filter (filtered sample), and an unfiltered aliquot was transferred to a 1-L polyethylene bottle for analysis.

Analysis of Runoff Water Samples. The runoff water samples collected at each event were analyzed for various forms of P as follows:

- Total P: determined on an aliquot of the unfiltered samples (semi-micro-Kjeldahl digestion; Bremner, 1996).

- DMRP: measured on the filtered sample.

The P concentration in all the aliquots was determined on a spectrophotometer using the molybdate blue method (Murphy and Riley, 1962).

The effect of cumulative P loading on the concentrations of the various forms of runoff P was evaluated by regression analysis to estimate the critical soil test P or P-loading threshold above which concentrations of runoff P increases significantly.

Results and Discussion

Soil Characteristics. Both mined and non-mined soils used in this experiment were degraded by intensive cultivation and/or grazing (Tian et al., 2009). In general, the predominant soil texture was fine silt loam, acidic pH, and very low organic carbon before the start of reclamation using biosolids (Table 3-1). Biosolids application to these fields varied from no application to as high as 1073 Mg ha^{-1} cumulative application during the 33 years of reclamation (Table 3-1). Application of biosolids led to an increase in soil organic carbon and cation-exchange capacity (CEC) and soil test P (Table 3-1), with increases proportional to biosolids application rates (Table 3-1). Detailed soil fertility improvements and carbon sequestration on these fields as a result of reclamation are discussed by Tian et al. (2009). Many other studies have also reported increases to the fertility status of soils receiving long-term application of biosolids (Brown and Leonard, 2004). Biosolids, like manure, have been well recognized as ideal amendments to increase soil organic matter (Paustian et al., 1997; Gilmour et al., 2003; Parat et al., 2005).

Relationship Between Biosolids Application and Potential for Losses of Soil Phosphorus. The simulated rainfall procedure used in this study simulated the worst case scenario of a runoff event with a rainfall intensity of 7 cm hr^{-1} 30-minute duration and antecedent soil saturation and no infiltration occurring during the rain storm. The probability of this rainfall intensity is very low in Illinois, as a 100-year 30-minute storm intensity is only 6.25 cm (NOAA, 2006). Also, the likelihood of field soils to be saturated before this kind of storm is low and rainfall water infiltrates into the soil continuously during the storm under natural field conditions.

Soil extractable P (Bray-1 P, Mehlich-3 P, Oxalate P, and WSP) increased with cumulative biosolids applications (Table 3-2). The changes in soil test P (Bray-1 P, Mehlich-3 P or WSP) were highly correlated with the cumulative biosolids application (R^2 = 0.80 to 0.87 (Figure 3-1). However, the increases in soil test P were not linear. Soil test P increased exponentially with cumulative biosolids application, approaching a maxima at higher cumulative biosolids application (Figure 3-1). It is well established that soil test P increases in areas where animal manures have been used for many years as fertilizer (Sharpley et al., 1996; Pautler and Sims, 2000). The present study is unique in that the cumulative biosolids application

TABLE 3-2: EFFECT OF BIOSOLIDS APPLICATION RATE ON CHEMISTRY AND EXTRACTABILITY OF SOIL PHOSPHORUS IN SOIL SAMPLES FROM FIELDS WHERE BIOSOLIDS WERE APPLIED TO STRIP-MINED AND NON-MINED FIELDS AT THE FULTON COUNTY SITE

Field No.	Type of Land	Sample Year	Cumulative Biosolids Applied	P-Ox[1]	Al-Ox[1]	Fe-Ox[1]	PSI	WSP[2]	Bray-1 P	Mehlich-3 P
			--- Mg ha^{-1}---	---------------- mg kg^{-1} ----------------				---------------- mg kg^{-1} ----------------		
10	NM	1974	0	212	1,204	3,923	6.0	3.0	12.7	27.6
	NM	1977	170	2,538	1,327	6,436	49.8	28.6	108.9	401.3
	NM	1979	300	4,001	1,839	8,881	56.9	34.7	110.0	531.7
	NM	2004	1,073	8,295	3,830	16,792	60.5	49.6	168.4	594.1
19	NM	1972	0	225	900	3,081	8.2	4.7	28.9	53.7
	NM	1979	263	2,592	1,489	7,514	44.1	28.8	115.1	459.8
	NM	1982	530	3,959	1,881	9,381	53.8	30.1	125.2	502.4
	NM	2004	641	3,339	1,782	8,189	50.7	39.1	153.8	533.6
20	NM	1972	0	254	951	3,007	9.2	8.3	26.0	51.0
	NM	1976	74	908	1,283	3,915	24.9	23.5	75.3	191.7
	NM	1981	325	2,914	2,018	6,780	48.0	44.4	110.7	462.9
	NM	2004	530	4,748	2,519	10,015	56.2	52.7	167.3	559.6
21	NM	1972	0	249	942	3,086	8.9	5.9	28.9	51.4
	NM	1975	64	988	1,014	4,595	26.6	15.5	45.7	132.2
	NM	1982	426	5,028	2,229	10,953	58.2	44.3	126.3	577.9
	NM	2004	614	4,341	2,045	9,913	55.4	51.1	160.6	587.0
22	NM	1972	0	158	1,029	2,813	5.8	6.7	16.7	30.8
	NM	1977	97	1,584	1,129	5,231	37.8	28.3	94.4	319.4

TABLE 3-2 (Continued): EFFECT OF BIOSOLIDS APPLICATION RATE ON CHEMISTRY AND EXTRACTABILITY OF SOIL PHOSPHORUS IN SOIL SAMPLES FROM FIELDS WHERE BIOSOLIDS WERE APPLIED TO STRIP-MINED AND NON-MINED FIELDS AT THE FULTON COUNTY SITE.

Field No.	Type of Land	Sample Year	Cumulative Biosolids Applied	P-Ox[1]	Al-Ox[1]	Fe-Ox[1]	PSI	WSP[2]	Bray-1 P	Mehlich-3 P
			--- Mg ha^{-1}---	----------------- mg kg^{-1} -----------------				----------------- mg kg^{-1} ----------------		
	NM	1980	236	4,311	1,872	9,277	59.1	44.9	121.3	552.5
	NM	2004	448	4,681	2,122	9,923	59.0	55.7	189.7	661.9
23	NM	1974	0	146	916	3,003	5.4	5.3	13.3	22.9
	NM	1977	56	364	1,103	3,251	11.9	5.9	36.4	94.1
	NM	1979	166	2,064	1,611	6,188	39.1	24.4	115.6	436.3
	NM	2004	473	4,912	2,480	10,550	56.5	53.7	167.3	570.0
31	NM	1974	0	570	1,163	4,190	15.6	1.3	12.6	22.0
	NM	1979	255	2,422	1,742	7,446	39.5	19.8	110.6	399.4
	NM	1981	389	3,066	1,898	8,225	45.5	29.8	138.6	507.7
	NM	2004	557	4,390	2,140	10,280	53.8	51.5	182.4	581.1
34	NM	1975	0	607	820	2,933	23.7	2.6	10.9	22.9
	NM	1978	153	2,811	1,400	6,924	51.6	25.7	113.4	454.7
	NM	1980	271	3,345	1,606	7,936	53.6	25.8	130.8	548.3
	NM	2004	566	5,058	2,253	10,331	60.8	54.8	184.1	677.2
40	MS + NM	1975	0	236	1,245	3,121	7.5	2.2	8.2	19.9
	MS + NM	1978	84	1,475	1,502	4,575	34.6	24.6	110.0	397.5
	MS + NM	1981	272	3,072	1,786	6,662	53.5	27.2	137.0	581.3
	MS + NM	2004	497	5,592	2,980	11,224	58.0	59.3	171.2	580.1

TABLE 3-2 (Continued): EFFECT OF BIOSOLIDS APPLICATION RATE ON CHEMISTRY AND EXTRACTABILITY OF SOIL PHOSPHORUS IN SOIL SAMPLES FROM FIELDS WHERE BIOSOLIDS WERE APPLIED TO STRIP-MINED AND NON-MINED FIELDS AT THE FULTON COUNTY SITE.

Field No.	Type of Land	Sample Year	Cumulative Biosolids Applied	P-Ox[1]	Al-Ox[1]	Fe-Ox[1]	PSI	WSP[2]	Bray-1 P	Mehlich-3 P
			--- Mg ha^{-1}---	----------------- mg kg^{-1} -----------------				----------------- mg kg^{-1} ----------------		
	NM	2004	497	3,807	2,004	7,866	57.1	49.4	179.1	691.5
51	MS	1987	0	230	926	3,367	7.9	5.4	17.4	41.2
	MS	2004	42	1,663	1,221	5,042	39.6	20.9	89.4	420.1
	MS	2004	42	534	914	3,218	18.8	9.9	55.8	171.7
59	NM	2004	0	264	841	3,015	10.0	5.1	26.5	55.4
75	MS	1979	0	252	743	1,946	13.1	1.1	2.1	7.1
	MS	2004	334	883	829	3,560	30.2	7.1	38.5	177.4
83	NM	2004	0	191	643	2,927	8.1	2.7	10.6	27.8

[1] Oxalate-extractable.

[2] Water-soluble P (1:25 soil:water ratio).

ND – Not determined.

rates were very high. The data in Figure 3-1, which shows soil test P reaching a maxima in response to cumulative biosolids, is expected because with long-term application, the proportion of biosolids to native soil present in the top 15 cm increases. At very high cumulative applications, the surface layer eventually may be composed mostly of biosolids, as shown previously in fields at the Fulton County site (Tian et al., 2009).

Biosolids contain appreciable amounts of Fe and Al (Table 3-1). Application of biosolids significantly increased the soil oxalate-extractable Fe and Al (Table 3-2). The oxalate-extractable Fe and Al are amorphous forms of Fe and Al oxides and relatively reactive due to their high surface area and thus may adsorb P very strongly. Oxalate-extractable P, Fe, and in soil Al have been used to calculate the PSI, which then has been related to the risk of P transport or losses from different soils (Maguire and Sims, 2002).

Various indices to estimate the degree of P saturation have evolved in recent years to predict the potential for P losses in runoff and leaching under field conditions (Breeuwsma et al., 1995; Sharpley, 1996; Pote et al., 1999; Sims et al., 1998). The greater the degree of P saturation, the higher the risk of P losses because these soils will have higher concentrations of adsorbed P. This greater P saturation of soil will lead to higher concentrations of soluble P in soil solution through desorption-dissolution reactions (Paulter and Sims, 2000). The primary objective of the present study was to estimate the cumulative biosolids loading above which the potential for P losses in biosolids amended soil increases significantly; or, in other words, find the biosolids loading required to increase soil test P to the critical environmental impact threshold above which the potential for runoff P losses from agricultural fields increases significantly. The data presented in Figure 3-2, showing relationships with PSI and WSP from the long-term biosolids application fields fitted to a Piecewise-2-Segment linear model, clearly demonstrate the critical change point at PSI = 31 and WSP = 10 mg kg^{-1}. Above this PSI, the response of WSP increases significantly.

The relationship between runoff P, WSP, and PSI from the simulated runoff study was evaluated by regression analysis. The relationship PSI vs. WSP and runoff P was fitted to a Piecewise-2-Segment linear model (Figure 3-3). The results show that the model fitted very well with the coefficient of determination values of 0.93 for PSI vs. WSP and 0.94 for PSI vs. runoff DMRP. The critical change point above which there was a rapid increase in WSP or runoff DMRP losses was a PSI of 37 and 40, respectively. Interestingly, these critical change PSI values were only slightly higher than the value of 31 determined in the laboratory study (Figure 3-2). Thus, for long-term biosolids application fields, the critical P saturation was between 30 to 40 percent based on oxalate extractable P, Al, and Fe; above this saturation point, there may be a greater risk of P losses to the water either via leaching to groundwater or via runoff to surface waters. In literature, the soil P saturation values above 25 to 40 percent are often associated with greater risks of P loss in leaching and runoff and thus non-point source pollution (Pote et al., 1999; Paulter and Sims, 2000).

The data in Figure 3-3 show PSI increases with cumulative biosolids loading and approaches a maximum above which biosolids loading has little effect on PSI. Within the plateau, soil P chemistry will be governed primarily by the biosolids and not by soil. The critical change point PSI values of 31 from the laboratory experiment (Figure 3-2) and 37 and 40 from the runoff simulation experiment (Figure 3-4) corresponded to cumulative biosolids application of 130 – 160 Mg ha^{-1}.

FIGURE 3-1: RELATIONSHIP OF CUMULATIVE BIOSOLIDS LOADING WITH MEHLICH-3 PHOSPHORUS, BRAY-1 PHOSPHORUS, AND WATER-SOLUBLE PHOSPHORUS FROM A LONG-TERM FIELD SITE

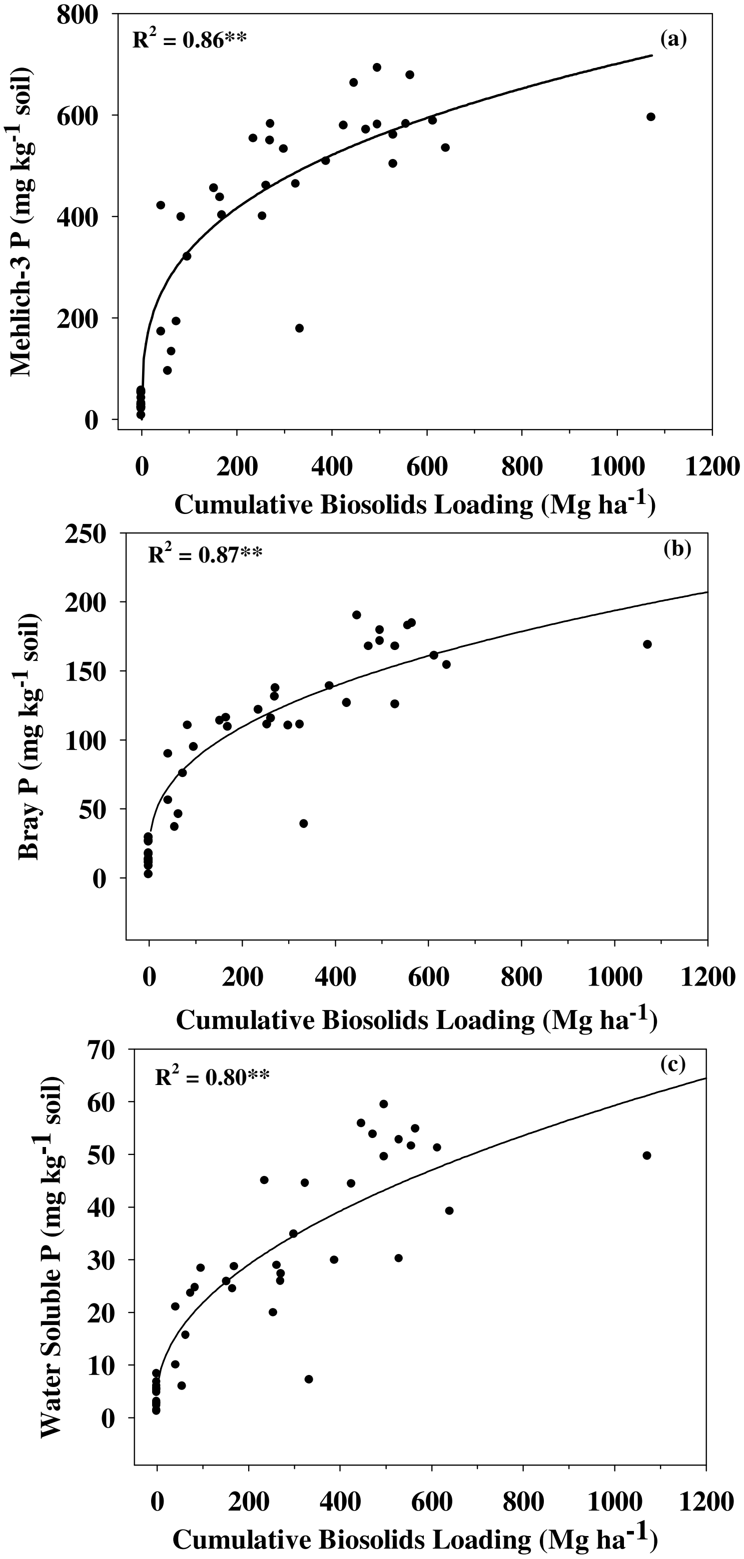


FIGURE 3-2: EFFECT OF PHOSPHORUS SATURATION INDEX OF SOILS WITH DIFFERENT CUMULATIVE BIOSOLIDS LOADING ON WATER-SOLUBLE PHOSPHORUS IN SOILS

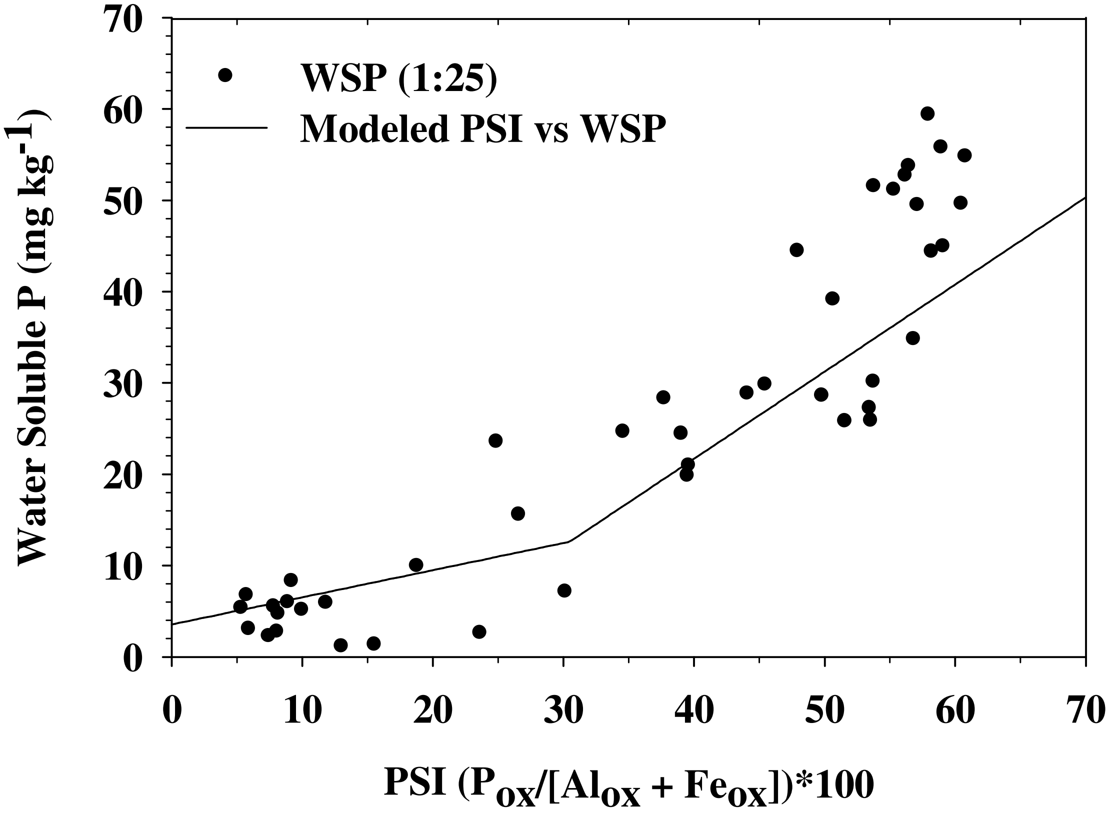


FIGURE 3-3: EFFECT OF BIOSOLIDS PHOSPHORUS LOADING ON SOIL PHOSPHORUS SATURATION INDEX

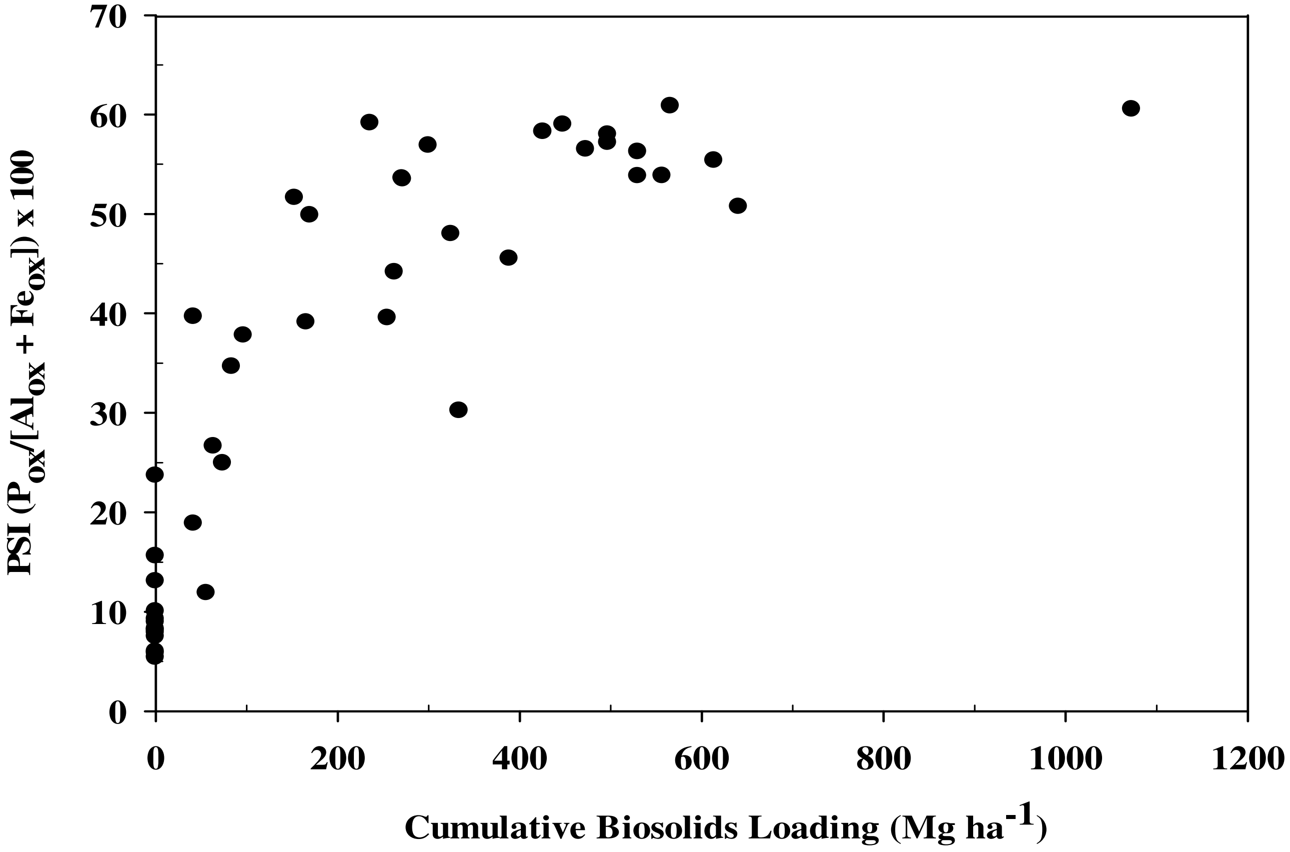
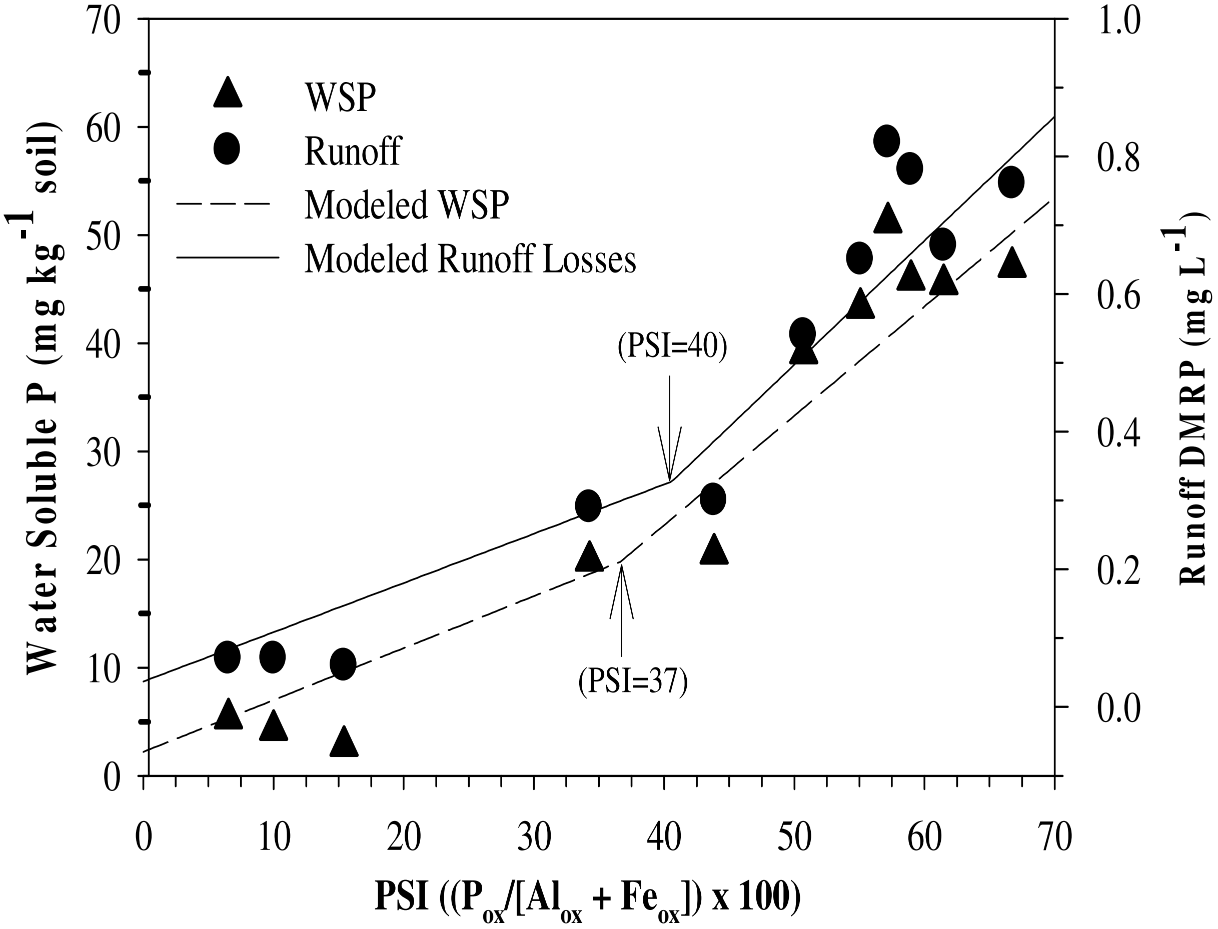


FIGURE 3-4: RELATIONSHIP BETWEEN PHOSPHORUS SATURATION INDEX OF 11 SOILS RECEIVING DIFFERENT BIOSOLIDS LOADING WITH WATER-SOLUBLE PHOSPHORUS AND RUNOFF PHOSPHORUS LOSSES DETERMINED BY RAINFALL SIMULATION



Conclusion

The results from this study show that repeated and long-term biosolids application up to a cumulative loading of 160 Mg ha^{-1} is safe with minimal risk of runoff P losses from the fields if agronomic best management practices are followed. Soils exceeding these biosolids loading rates or having P saturation greater than 40 percent may require greater management practices to minimize P loss from the fields. These management practices may involve: (1) cessation of biosolids application for a few years to bring the P saturation below the critical level, (2) application of biosolids at a reduced rate based on crop P removal, and (3) adoption of management practices such as reduced tillage, buffer strips, and grassed waterways.

CHAPTER 4

USING SIMULATED RAINFALL TO DETERMINE PHOSPHORUS LOSS IN SURFACE RUNOFF FROM BIOSOLIDS AMENDED SOIL

Abstract

Intensive agriculture typically relies on fertilizers and organic sources of nutrients, like animal manures and biosolids, to maximize yields. Over applications of P generally increase the potential for P losses through runoff to surface water. In this study, we compare P losses in runoff generated by simulated rainfall from soil receiving TSP applied at the recommended agronomic rate with two types of biosolids (Class B CC and Class A lagoon-aged and AD) either surface applied or incorporated at rates equivalent to crop N (N-based) or P (P-based) requirements. The rainfall simulations used the NPRP approach. Runoff samples were analyzed for dissolved reactive phosphate (DRP), particulate P, and TP. The P source significantly affected the DRP concentration in runoff: TSP > AD biosolids > CC biosolids; the DRP concentrations ranged from 0.04 to 0.82 mg L^{-1}. Significantly greater TP concentrations (ranging from 5.7 to 13.0 mg L^{-1} for three runoff events) were observed when CC biosolids were surface applied at an N-based rate than all the other treatments. Particulate P accounted for the major P losses, and both particulate P and TP losses were significantly greater from CC biosolids than from AD biosolids or TSP. The N-based biosolids rate (surface applied) produced greater runoff P losses than the P-based application rate; the DRP losses in runoff were reduced by 80 percent, and particulate P and TP losses were reduced by 33 percent when biosolids were applied at P-based rather than N-based application rates. Incorporation of biosolids applied at N-based application rates reduced the DMRP losses by 50 percent and particulate P and TP losses by approximately 33 percent compared to surface application and effectively reduced runoff P losses to the levels similar to the mean P-based biosolids application rates.

Objective

The main objective of conducting the present study was to estimate and compare the potential for P losses in soil amended with Class B CC (~25 percent solids), Class A lagoon-aged, AD biosolids (~70 percent solids), and TSP fertilizer using simulated rainfall.

Materials and Methods

Soil and Study Site. Bulk, air-dried, and sieved (2 mm) Sable silty clay loam soil (fine-silty, mixed, superactive, mesic *Typic Endoaquoll*) from a field at the District's Fulton County land reclamation site was used for this study. The study site has a continental climate and is located at Fulton County in Western Illinois, approximately 300 km southwest of Chicago, with an annual mean air temperature of 10.4°C and annual precipitation of 1,013 mm. Prior to taking soil samples, the field was cropped with corn without P fertilization for three years (2003 - 2005) to deplete soil P. A bulk surface soil sample collected in the fall of 2005 showed that the soil was P deficient with only 13.9 mg kg^{-1} (Bray-1 P) and 26.0 mg kg^{-1} Mehlich-3 P (Illinois Agronomy Handbook, 2009). Other soil characteristics were: soil pH of 6.3, 16.5 g kg^{-1} organic C, 12.3 percent sand, 61.7 percent silt, and 26 percent clay.

Biosolids. The biosolids used in this study were anaerobically digested Class B CC biosolids and Class A AD biosolids generated at the District's Calumet WRP. Selected properties of the biosolids used in this study are given in Table 4-1.

Treatments. In this study, the NPRP protocol (NPRP, 2006), as described below, was employed to determine the potential for P runoff from the soil immediately following the application of biosolids and TSP.

The treatments consisted of the following: three P sources (AD biosolids, CC biosolids, and TSP); two P rates, which were the amounts of P associated with biosolids rates applied to meet corn N or P requirements (N-based or P-based); and two methods of application, either surface application or application followed by incorporation; however, TSP was only incorporated. The experiment was set up as a completely randomized block design with 3 replications and 11 treatments (8 combinations of biosolids type, rate, and application method, 2 TSP rates, and 1 control).

The amounts of biosolids and TSP rates approximated the standard fertilizer practices in the region where the typical agronomic rate of N and P for corn is 224 kg N ha^{-1} yr^{-1} and 45 kg P ha^{-1} yr^{-1}, respectively. The amounts of P added in soil used for rainfall simulation from N-based and P-based application of CC biosolids were 292 mg P and 20 mg P kg^{-1} dry soil, respectively (Table 4-1). The amount of AD biosolids needed to apply the amount of P (292 mg P kg^{-1}) at the N-based rate was higher than the amount of CC biosolids, because total P in AD biosolids was lower than in CC biosolids (Table 4-1). Surface application of biosolids consisted of spreading the biosolids on the soil surface in trays uniformly, and incorporation of biosolids consisted of the mixing of biosolids in the surface 2 cm soil layer with a wooden spatula after spreading uniformly on soil surface in the trays.

Rainfall Simulation. The soil trays were constructed from galvanized sheet metal according to the approach used in the NPRP protocol (NPRP, 2006). The inside dimensions of the trays were 100 cm long x 20 cm wide x 7.5 cm high (the down-slope side of the tray was only 5 cm high). The bottoms of the trays were lined with cheesecloth, since they had holes in the bottom, and then the amount of soil required to fill the trays to 5 cm deep at 1.5 Mg m^{-3} bulk density was packed with the aid of a wooden damper. Water was added slowly to the soil in the trays until they were saturated. The saturated trays were covered with plastic to minimize moisture loss and left to drain and equilibrate for one day before the simulated rainfall was applied to the soil. At the down-slope end of the tray, a V-shaped trough was attached to collect runoff. A metal frame was constructed to support up to eight of the soil trays at approximately 45 cm above the ground. The frame was designed such that the trays could be tilted at various angles to simulate different slopes.

TABLE 4-1: PHYSICAL AND CHEMICAL CHARACTERISTICS OF BIOSOLIDS USED IN THE SIMULATED RUNOFF STUDY

Parameter	Units	Centrifuge Cake Class B Biosolids	Lagoon Aged, Air-Dried Class A Biosolids
Solids	%	29.70	70.33
Wet Bulk Density	Mg m^{-3}	0.74	1.19
pH		8.02	6.63
TKN	g kg^{-1}	38.74	16.34
NH_4 +NO_3-N	"	14.06	5.09
TP	"	16.80	14.59
Al	"	22.69	22.80
Fe	"	17.11	20.25
Ca	"	32.34	43.82
Mg	"	14.22	17.93
K	"	4.10	3.93

The rainfall simulator (Joern's Inc., West Lafayette, IN) is similar to that described for the NPRP studies. The simulator consists of piping, an electrical pump, a pressure gauge, and a TeeJet 1/2 HH SS 50 WSQ nozzle (Spraying Systems Co, Wheaton, IL) mounted on an Al frame (2.3 m wide x 2.8 m long x 3 m high) and covered with a plastic tarp to provide a windscreen. A polyethylene tank was used to store enough water for each simulated rainfall event. The rainfall simulator was set up on the ground of the laboratory at the Fulton County site. Reverse osmosis water with approximate pH 6.7 and the TP content less than 0.01 mg P L^{-1} was used for the rainfall simulation. The flow meter was calibrated to deliver water at a rate equivalent to 70 mm hr^{-1} (specified in the NPRP protocol) over the area covered by a spray nozzle. This intensity is equivalent to a 100-year storm in the Midwest United States (Hershfield). The packed trays were randomly placed on the metal frame at an angle equivalent to a 4-percent slope. Pre-weighed, approximately 4.0-L capacity plastic bottles equipped with funnels were placed under the collection trough at the down-slope end of the trays for collecting runoff generated during each 30-minute event. Three runoff events were conducted; for each event, the initial 30 minutes of runoff was collected and a subsample immediately filtered (0.45 μm) and acidified (pH<2). The first runoff event was conducted after 24 hours of saturation, and the second and third events were conducted at three and seven days after the first event, respectively. The trays were kept covered with a polyethylene sheet between runoff events.

Analysis of Soil and Runoff Water Samples. The runoff water samples collected at each runoff event were analyzed for various forms of P as follows: TP was determined from an aliquot of the unfiltered samples (semi-micro-Kjeldahl digestion; Bremner, 1996); DRP was measured from the filtered sample. The P concentration in all samples was determined by a spectrophotometer using the molybdate blue method (Murphy and Riley, 1962).

Analysis of Biosolids. Total trace elements in the biosolids samples were extracted by acid digestion using USEPA Method 3050 (USEPA, 1996). Trace elements in the digests and extracts were analyzed by inductively coupled plasma-atomic emission spectrometry (ICP-AES) (USEPA, 1996). Total N and P in the biosolids samples were extracted by sulfuric acid digestion and measured using the Kjeldahl procedure (Bremner 1996) and the modified ascorbic acid method (Murphy and Riley, 1962), respectively. Wet bulk density of biosolids was measured just before use by adapting the procedures by Glancey and Hoffman (1996).

Statistical Analysis. Particulate P was calculated from the difference in concentration of TP and DRP. The data were subjected to analysis of variance at the 0.05 probability level and Duncan's multiple-range posteriori test using SAS procedures (Littell et al., 1996).

Results and Discussion

Biosolids Characteristics. The physico-chemical characteristics of biosolids used in this study are presented in Table 4-1. Total Kjeldahl nitrogen and TP concentrations were higher in CC biosolids. The concentrations of elements like Al, Fe, Ca, and Mg were higher in AD biosolids. The wet bulk density of CC biosolids was significantly less (0.74 Mg m^{-3}) than that of AD biosolids (1.19 Mg m^{-3}). The difference in bulk density between different types of biosolids may play an important role in controlling the loss of particulate matter in runoff water after land application of biosolids. O'Connor and Elliott (2006) also noticed this phenomenon when comparing different types of biosolids and showed that cake-type biosolids (low solids content) are easily scoured from the soil surface, causing more suspension of biosolids materials and loss in runoff.

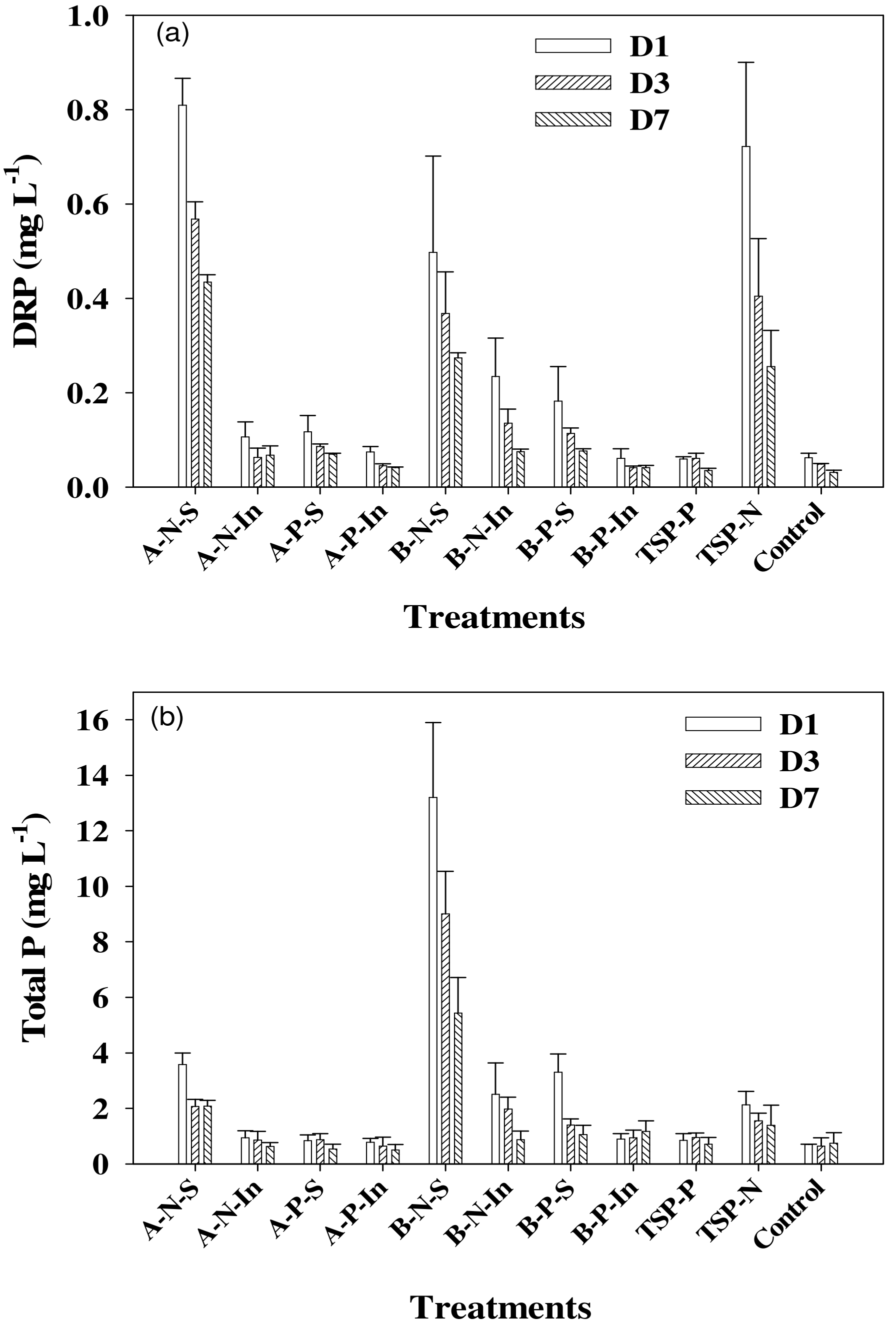
Runoff Losses of Phosphorus. The rainfall simulation following the NPRP protocol was conducted on days D1, D3, and D7 after soil was amended with biosolids and TSP. The data on flow-weighted DRP and TP concentrations for the three runoff events are presented in Figure 4-1. Higher amounts of both DRP and TP were observed in the simulated runoff on D1 (Figure 4-1) but declined on D3 and D7. The concentration of DRP in runoff ranged from as low as 0.04 mg L^{-1} to as high as 0.82 mg L^{-1}. In general, higher DRP and TP concentrations occurred at the N-based rate and when biosolids were surface applied rather than incorporated (Figure 4-1). Significantly higher TP concentrations (ranging from 5.7 to 13.0 mg L^{-1}) in runoff for all three rainfall events occurred for N-based, surface-applied CC than AD and TSP treatments. This could be attributed to a loss of biosolids in surface runoff from CC biosolids-amended soil due to the significantly lower bulk density of CC biosolids (Table 4-1). Chunks of biosolids were observed floating in runoff water during the runoff simulation events. The concentrations of TP in runoff from biosolids were within the range of ~3.0 to 27.5 mg L^{-1} reported for 10 different biosolids in studies conducted by Elliott et al. (2005). In general, Elliott et al. (2005) and O'Connor and Elliott (2006) found higher P losses from biosolids obtained from facilities employing enhanced biological P removal and with lower Fe and Al concentrations.

The data on P concentrations in runoff and runoff volumes for all three runoff events were combined to estimate the P losses expressed as mg P $tray^{-1}$ for all treatments; the analysis of variance test showed that all three measured fractions of P in runoff (DRP, particulate P, and TP) were affected by the P source method and rate of application. Treatment interactions were not significant (Table 4-2).

The source of P significantly affected DRP losses in the order of TSP > AD biosolids > CC biosolids (Table 4-3). Higher DRP losses from TSP treatments are attributed to higher solubility of TSP fertilizer. Higher DMRP losses from inorganic P fertilizer, as compared to broiler litter, were previously reported by Edwards and Daniel (1994). However, particulate P accounted for major P losses in runoff, and both particulate P and TP losses were significantly higher for CC biosolids as compared with AD biosolids and TSP, which could be attributed to the low bulk density of CC biosolids as stated above (Table 4-3). Tarkalson and Mikkelsen (2004) compared losses of P from broiler litter and inorganic P fertilizer and also reported that mass losses from broiler litter were four to seven times higher than from inorganic P fertilizer applied at the same P rates, most likely due to lower bulk density manure particles being transported in runoff.

The method of application of biosolids also affected the runoff P loss; incorporation of biosolids significantly reduced the runoff P losses as compared to surface application (Table 4-4). Incorporation of biosolids reduced DRP losses by 50 percent and particulate P and TP losses by approximately 33 percent (Table 4-4). Studies using manures as a P source showed similar reductions in runoff P losses when manures were incorporated in the soil after application rather than surface application (Mueller et al., 1984; Ginting et al., 1998; O'Connor and Elliott, 2006; Agyin-Birikorang and O'Connor, 2008). Phosphorus from cropland is generally

FIGURE 4-1: FLOW-WEIGHTED CONCENTRATION OF DISSOLVED REACTIVE PHOSPHORUS AND TOTAL PHOSPHORUS DURING THREE RUNOFF EVENTS AS AFFECTED BY TYPE OF BIOSOLIDS, MANAGEMENT, AND RATE OF APPLICATION



Note: (a) = dissolved reactive phosphorus; (b) = total phosphorus; A = AD; B = CC; S = surface-applied; I = Incorporated; N = N-based; P = P-based; TSP = triple superphosphate;

TABLE 4-2: ANALYSIS OF VARIANCE FOR LOSS OF PHOSPHORUS IN RUNOFF AS AFFECTED BY PHOSPHORUS SOURCE, MANAGEMENT, AND RATE OF PHOSPHORUS APPLICATION

Source	DRP	Particulate P	Total P
P Source (AD, CC, TSP)	*	*	*
Management (Surface or Incorporated)	*	*	*
P Rate (N-based or P-based)	*	*	*
Interactions			
P Source x Management	NS	NS	NS
P Source x P Rate	NS	NS	NS
Management x P Rate	NS	NS	NS
P Source x Management x P Rate	NS	NS	NS

*Significant at $P \leq 0.05$; NS = Non-significant.

TABLE 4-3: LOSS OF RUNOFF PHOSPHORUS AS AFFECTED BY SOURCE OF PHOSPHORUS APPLIED ACROSS MANAGEMENT AND APPLICATION RATE

P Source	DRP	Particulate P	Total P
	----------------------------	mg tray^{-1}	------------------------------
AD Biosolids	3.17b[1]	13.59b	18.76b
CC Biosolids	2.66c	47.71a	53.26a
TSP	4.04a	13.52b	19.30b

[1] Data followed by a different letter within a column are significantly different at $P \leq 0.05$.

TABLE 4-4: LOSS OF RUNOFF PHOSPHORUS AS AFFECTED BY MANAGEMENT ACROSS SOURCE OF PHOSPHORUS AND RATE OF APPLICATION

Management	DRP	Particulate P	Total P
	---------------------------- mg tray^{-1}	----------------------------	
Surface Applied	4.50a[1]	46.91a	54.40a
Incorporated	2.24b	14.10b	18.18b

[1] Data followed by a different letter within a column are significantly different at P ≤0.05.

either as soluble P or particulate P attached to particles of soil or organic by-products such as manures and/or biosolids. As much as 90 percent of the P transported from cropland was bound to soil particles (Sharpley and Beegle, 1999). Erosion control measures may prevent significant P losses from cropland. The present study clearly showed that incorporation of biosolids significantly reduced both the DRP and particulate P concentrations in runoff (Figure 4-1). However, soil disturbance resulting from biosolids incorporation may increase soil erosion, especially in fields with higher slopes or erosion-prone soils and may have a negative impact on soil and water quality. Biosolids application on highly eroded soils and fields with higher slopes (>8 percent) is prohibited under the Part 503 Rule (USEPA, 1994).

Our results show that N-based biosolids application led to significantly higher P losses in runoff as compared to the P-based application rate, regardless of the type of biosolids (Table 4-5). The DRP losses in runoff were reduced by about 80 percent and particulate P and TP losses by ~33 percent when biosolids were applied at P-based rather than N-based rates (Table 4-5). Similarly, higher runoff P concentrations and mass losses have been reported for manures at typical N-based application rates as compared to P-based rates (Tarkalson and Mikkelsen, 2004).

Runoff data generated from rainfall simulations using packed trays have some shortcomings. For example, a greater amount of runoff is generated from packed trays as compared to that from the field (Potter et al., 1995; Thompson et al., 2001; Guidry et al., 2006). Nonetheless, simulated rainfall runoff studies are useful in developing relationships between the soil test P and runoff P losses (McDowell and Sharpley, 2001; Kleinman et al., 2004). The present study has provided valuable information regarding the use of simulated runoff and packed trays to describe P losses from biosolids for devising effective P management strategies in biosolids-amended fields.

Conclusion

Our results show that incorporation of biosolids applied at N-based rates could reduce the runoff P losses to levels similar to P-based application rates. Thus, incorporation of biosolids immediately following application is a very effective management practice to reduce the risk of transport of particles (soil or biosolids) in erosion and runoff P losses.

TABLE 4-5: LOSS OF RUNOFF PHOSPHORUS, mg TRAY^{-1}, AS AFFECTED BY PHOSPHORUS RATE ACROSS MANAGEMENT AND PHOSPHORUS SOURCE

P Rate	DRP	Particulate P	Total P
	------------------------- mg tray^{-1}	-------------------------	
N-based	5.52a[1]	37.49a	45.53a
P-based	1.06b	12.39b	15.35b

---

[1] Data followed by a different letter within a column are significantly different at $P \leq 0.05$.

CHAPTER 5

PHOSPHORUS RUNOFF LOSSES IN BIOSOLIDS-AMENDED SOIL AND CONTROL BY VEGETATED BUFFER STRIPS

Abstract

Results from many published field studies and simulated runoff studies showed that most of the P losses from farmland are in the form of particulate P, so reducing the loss of soil particles due to erosion may provide a solution to reducing P losses in runoff. One of the best management practices often employed to reduce transport of soil by surface runoff is installing vegetative buffer strips at the edge of cropped fields. Field studies were conducted at the Fulton County site to evaluate the effectiveness of vegetated buffer strips (consisting of a mixture of alfalfa and bromegrass) for controlling P runoff losses from biosolids-amended soil. Plots were established with treatments of CC biosolids at 22.4 Mg ha^{-1} (235 kg P ha^{-1}) and TSP (52 kg P ha^{-1}). Results showed that vegetative buffer strips were very effective in reducing the transport of particulate matter. On average, approximately 76 percent sediment reduction was observed when the buffer strip width was 7.6 m, and doubling the buffer strip to 15.2 m only marginally increased sediment reduction to 85 percent. The results showed that the concentration of DMRP in runoff was not reduced by vegetated buffer strips for both years. However, a buffer strip width of 7.6 m was enough to reduce the runoff total P concentration during both the snowmelt and rainfall runoff events. Averaged over two years, a 7.6 m buffer was sufficient to reduce the total P concentration below 1 mg L^{-1} from treatments with biosolids application. In terms of P load, the width of buffer strip only marginally reduced DMRP losses from both TSP and biosolids treatments. However, significant reduction in Total P occurred for both years, and effects were significant during rainfall runoff events compared to snowmelt runoff events. The results showed that a 7.6 m wide buffer could control a majority (50 to 75 percent) of losses in total P, and doubling the buffer width to 15.2 m only marginally reduced total P losses further. The results are in agreement with the 10.7-m wide buffer strip recommended in the Illinois Nutrient Reduction Strategy, and results from many published literature which indicate that a 5 to 10-m buffer width is sufficient to reduce both sediment and phosphorus losses from biosolids-applied fields. Establishment of vegetative buffer within the 10-m setback from surface water required under the 40 CFR Part 503 rule for land application of biosolids (USEPA, 1993) should be sufficient to protect surface water from runoff P contamination.

Objectives

The overall objective of this study was to evaluate the use of buffer strips in reducing P losses from land-applied biosolids.

The specific objectives are:

1. To compare the potential for P runoff from soil amended with District biosolids and inorganic fertilizer.

2. To evaluate the effectiveness of two widths (7.6 m and 15.2 m) of vegetated buffer strips established in the setback zones of land application fields in controlling P runoff from fields amended with District biosolids and inorganic fertilizer.

Materials and Methods

Description of Study Site and Plot Layout. The study was conducted on mine-spoil soil at the District's Fulton County Land Reclamation Project site. The study area is located on a 60-ha mine-spoil area designated as Field 63-8, which has a gently rolling topography. We selected portions of the field that had the most consistent slopes and were large enough to establish the desired plot size. We selected six non-contiguous 0.74-ha areas that were approximately 122–m long (along the slope) by 61-m wide as the main plots. The slopes within these areas ranged from 2 to 4 percent. The land preparation and the layout of the plots were done in early spring 2004. The existing forage crops on the main plots were mowed, and then uneven portions of the main plots were graded to improve the uniformity of the slope within each main plot. The grading is expected to have very little effect on the chemical characteristics of the surface soil because the soil in this field has a relatively uniform profile within the upper 90-cm. The grading operation was observed closely so that heterogeneity in the characteristics (such as compaction and presence of voids) that can potentially affect the surface hydrology of the plots was minimized. Corn was grown in this field until runoff experiments were set up in 2007. The six areas were marked out and received TSP or biosolids applications according to treatments in 2007. These selected areas were separated by earthen berms, approximately 0.3 m high by 1 m wide to isolate the runoff entering these areas from surrounding fields.

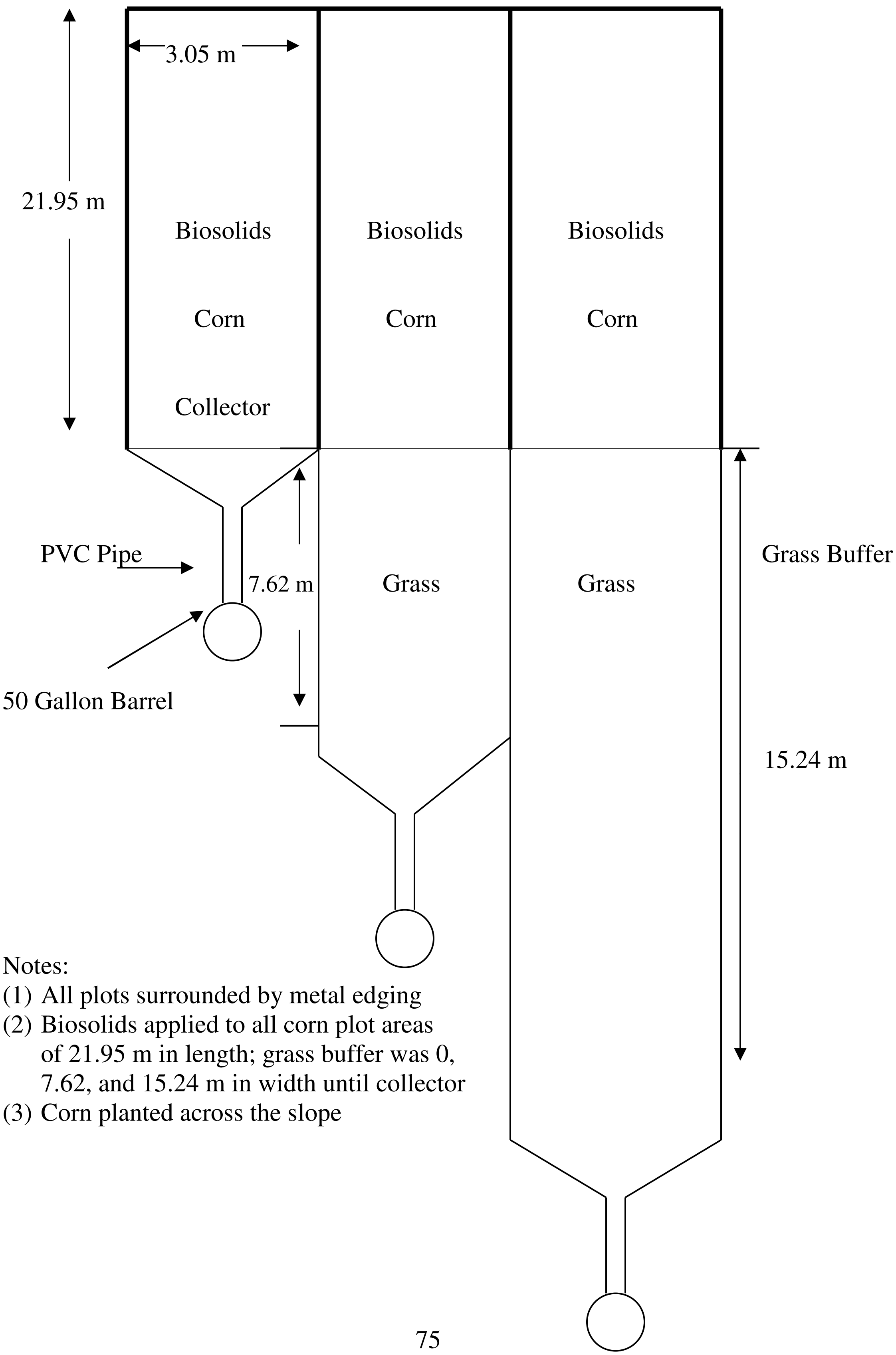
A total of 18 standard runoff subplots 21.95 m x 3.05 m were set up, three within each of the six areas. Each runoff plot was separated with metal edging and runoff flow directed towards a metal collector set up as shown in Figure 5-1 and Photograph 5-1. The metal edging enclosure for each set of runoff plots included three widths of grassed buffer strips (0, 7.62 m, and 15.24 m) towards the lower side of plots. More information about runoff plot set-up and runoff collection system is provided in Kumar et al. (2009). A corn crop was planted in May of 2008 and 2009 and harvested in late October of both years.

Study Design and Treatments. The study consisted of three replicates of the following treatments:

Two P Sources:

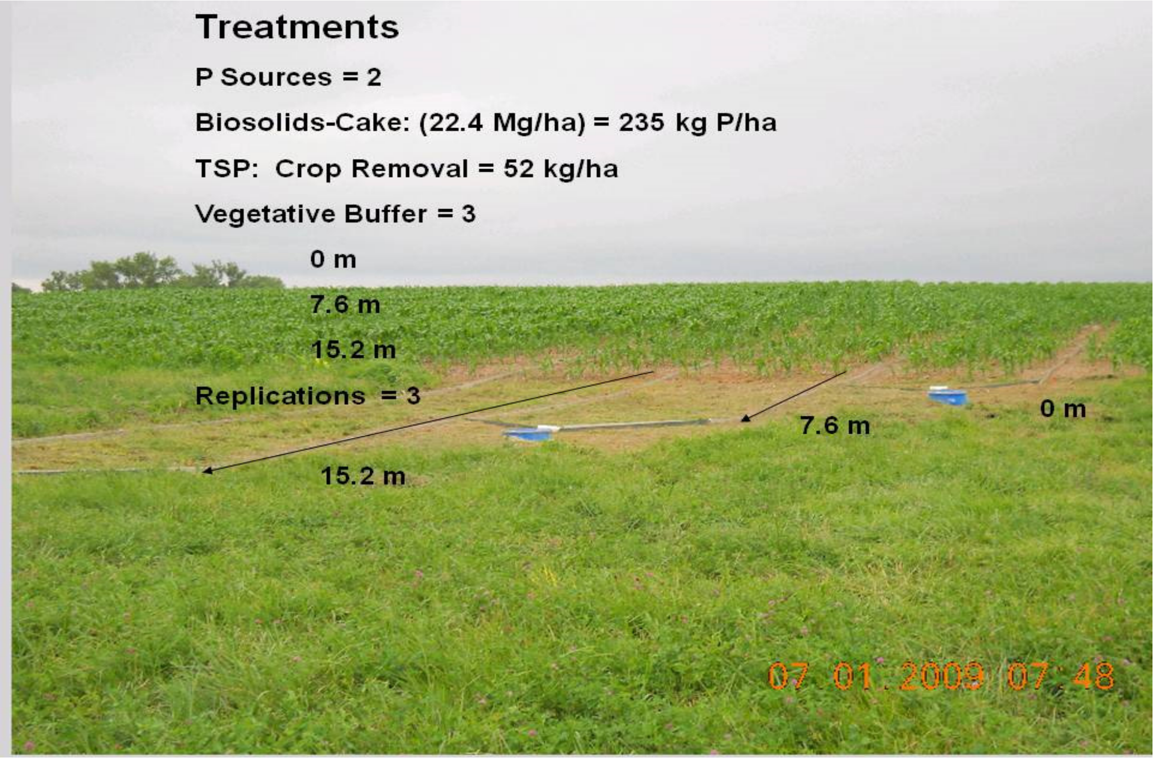
1. Anaerobically digested Class B CC biosolids at 22.4 Mg ha^{-1} (10 dry tons ac^{-1}) (210 lbs P ac^{-1} or 235 kg P ha^{-1}).
2. Triple superphosphate fertilizer equivalent to annual crop removal (46 lbs P ac^{-1} or 2 kg P ha^{-1}). This treatment also received N (234 lbs ac^{-1} or 262 kg ha^{-1}) and K (410 lbs ac^{-1} or 460 kg ha^{-1}) fertilizer.

FIGURE 5-1: SKETCH OF RUNOFF PLOTS DESIGN



Notes:
(1) All plots surrounded by metal edging
(2) Biosolids applied to all corn plot areas of 21.95 m in length; grass buffer was 0, 7.62, and 15.24 m in width until collector
(3) Corn planted across the slope

PHOTOGRAPH 5-1: PHOTOGRAPHS SHOWING THE PLOT LAYOUT AND THE RUNOFF COLLECTION SYSTEM



Treatments

P Sources = 2

Biosolids-Cake: (22.4 Mg/ha) = 235 kg P/ha

TSP: Crop Removal = 52 kg/ha

Vegetative Buffer = 3

0 m

7.6 m

15.2 m

Replications = 3

Three widths of vegetated buffer strip:

1. 0 m (edge of field)
2. 7.6 m
3. 15.2 m

Vegetated Buffer Strips. The vegetated buffer area was prepared by establishing a mixture of alfalfa (*Medicago sativa* L.) and bromegrass (*Bromus inermis*) on the entire length of the down-slope portion (60 m downslope x 61 m across slope) of the main plots, while P treatments were applied to the up-slope portion (60 m x 60 m) of the plots planted with corn. The two widths of vegetated buffer strips were established by installing run-off collection devices 7.6 m and 15.2 m down from the edge of the corn plots. The vegetated buffer was planted and allowed to establish before the P treatments were applied. The vegetation in the buffer area received an agronomic rate of nitrogen fertilizer only in the first year of the establishment; and for the remainder of the study, no additional fertilizer was applied. During the study, the vegetation was mowed periodically to a height of about 15-cm.

Runoff Collection and Analysis. Runoff was collected after each rainfall or snowmelt event for two years. The runoff collected was analyzed for total sediments (suspended solids), TP on an aliquot of the unfiltered samples (semi-micro-Kjeldahl digestion; Bremner, 1996), and DMRP on the filtered sample. The P concentration in all samples was determined by a spectrophotometer using the molybdate blue method (Murphy and Riley, 1962).

Results and Discussion

Precipitation and Runoff. Monthly precipitation and runoff volumes for the two years of the study period are presented in Table 5-1. In general, there was not much difference in runoff volumes from biosolids or TSP plots. The amount of runoff generated depended on the storm intensity and duration.

Sediment Retention. Sediment retention was calculated as the difference between the suspended solids concentration in runoff and snowmelt samples collected for the two buffer widths and at the edge of the corn plots (0 buffer width). Data in Table 5-2 show that in general, biosolids treatment showed lower sediment mass loss during both years. In addition, a buffer strip length of 7.6 m was sufficient to reduce a majority of sediment mass loss, and doubling that width only marginally reduced further sediment loss, indicating that most of the particulate matter was captured within the first few meters of buffer width. The effectiveness of the buffer strip in reducing sediment loading was much greater in snowmelt runoff (> 90 percent) as compared to rainfall runoff (74-86 percent), probably due to the slow velocity of snowmelt runoff as compared to rainfall runoff. The average sediment retention for the 7.6 and 15.4 m buffer widths and comparison to literature values are presented in Table 5-3. The average sediment reduction during two years was 76 percent at 7.6 m buffer width and

TABLE 5-1: MONTHLY PRECIPITATION AND RUNOFF AT THE EDGE OF THE CORN FIELD DURING THE STUDY PERIOD

	2008			2009		
		Runoff			Runoff	
Month[1]	Precip.	TSP	Biosolids	Precip.	TSP	Biosolids
	-----cm ----	------------ (cm)[2] -----------		-----cm ----	------------ (cm)[2] -----------	
January	7.30	0.00	0.00	8.20	0.00	0.00
February	6.30	1.30	1.10	8.23	0.60	0.55
March	3.70	0.90	0.90	14.30	1.50	1.35
April	9.20	0.40	0.47	15.80	0.94	0.74
May	4.68	0.40	0.46	13.88	1.15	0.95
June	6.85	0.55	0.52	7.38	0.45	0.42
July	6.28	0.42	0.41	16.80	1.56	1.30
August	5.53	0.68	0.62	11.48	0.70	0.62
September	22.58	1.35	1.28	5.28	0.20	0.18
October	7.93	0.20	0.24	14.15	0.50	0.19
November	0.45	0.00	0.00	0.58	0.00	0.00
December	4.63	0.00	0.00	2.36	0.00	0.00

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[1] Rainfall events > 1.25 cm only generated any runoff and are reported as cumulative for that month.

[2] Calculated based on the plot areas and runoff volumes collected at the edge of the corn plots (0 m buffer).

TABLE 5-2: REDUCTION IN SEDIMENT LOSS IN RELATION TO WIDTH OF THE VEGETATED BUFFER STRIP

Buffer Width (m)	2008 Sediment Loss				2009 Sediment Loss			
	TSP	Biosolids	TSP	Biosolids	TSP	Biosolids	TSP	Biosolids
Snowmelt Runoff								
	kg ha^{-1}		% Reduction[1]		kg ha^{-1}		% Reduction[1]	
0	199.1	137.5			91.0	39.9		
7.6	14.6	11.0	93	92	6.3	2.7	93	93
15.2	10.7	8.7	95	94	4.4	2.5	95	94
Rainfall Runoff								
0	1,500.0	1,256.0			1,507.0	1,150.4		
7.6	385.9	300.5	74	76	379.0	249.0	75	78
15.2	312.5	188.9	79	85	245.6	165.4	84	86
Snowmelt + Rainfall Runoff								
0	1,699.1	1,393.5			1,598.0	1,190.3		
7.6	400.5	311.5	76	78	385.3	251.7	76	79
15.2	323.2	197.6	81	86	250.0	167.9	84	86

[1] Percent reduction calculated in relation to edge of field, i.e. 0 m buffer width.

TABLE 5-3: WIDTH OF GRASS BUFFER STRIPS AND SEDIMENT RETENTION

Width (m)	Sediment Retention (%)	Reference
-------------------------------------	Rain Runoff	---
15.2	85	Present study (two-yr. average)
7.6	76	Present study (two-yr. average)
-----------------------------------	Snow-Melt Runoff	-------------------------------------
15.2	95	Present study (two-yr. average)
7.6	93	Present study (two-yr. average)
-------------------------------------	Literature Values	-------------------------------------
91.5	80	Castelle et al., 1994
26.2	80	
22.4	92	
9.1	84	
4.6	70	
18.3	94	Lim et al., 1998
12.2	90	
6.1	70	

increased to only 85 percent with doubling the buffer width. These results corroborate the findings of many field studies that nutrient losses from fields do not increase linearly with the vegetation buffer width (Dorioz et al., 2006). This suggests that for the effectiveness of grass buffer strips in reducing sediment, there is an optimum width beyond which there is little further increase in the effectiveness of buffers (Castelle et al., 1994; Lim et al., 1998). This optimum width can be as narrow as 1 – 2 m to significantly reduce sediment and nutrient losses (Abu-Zreig et al., 2003; Vallieres, 2005). Recommended widths for vegetative buffer strips are variable, as illustrated by the doubling of standard widths recommended by the Soil Conservation Service (SCS) of the USA (now NRCS, Table 5-4) from 1988 to 1990 and then again from 1990 to 1997 (SCS 1988; SCS 1990; SCS 1997). The reason for this increase was to reduce nutrient losses in addition to sediments due to erosion. The detailed studies of Dillaha et al. (1989) and of Magette et al. (1989) resulted in the similar conclusion that most of the sediments in field runoff (53 – 86 percent of the input load) are retained in the first 5 m buffer. Farther down slope, beyond 5 – 10 m, the quantities retained are smaller (five to six times less). The science assessment of the Illinois Nutrient Loss Reduction Strategy recommends a 10.7 m vegetated buffer for controlling P runoff from agricultural land (IEPA 2015).

Phosphorous Concentration. The concentration of DMRP was not reduced with increasing the buffer width during both snowmelt and rainfall runoff events for both years. However, a buffer width of 7.6 m was enough to reduce the runoff total P concentration during both the snowmelt and rainfall runoff events. (Table 5-5). Based on the average over two years, a 7.6 m buffer was sufficient to reduce the TP concentration from 2.2 mg L^{-1} to less than 1 mg L^{-1} from biosolids-applied plots.

Phosphorus Losses. Losses of runoff P for various treatments as a function of buffer width are presented in Table 5-6. The width of buffer strip only marginally reduced DMRP losses from both TSP and biosolids treatments. However, significant reduction in Total P occurred for both years, and effects were significant during rainfall runoff events compared to snowmelt runoff events (Table 5-6). A major reduction was observed within the buffer width of 7.6 m. Since buffer strips captured the majority of sediments within the 7.6 m buffer area, as shown earlier (Table 5-2), the reduction from 7.6 m to 15.2 m buffer width was relatively lower. The sediment rate is correlated with particulate P (Blanco-Canqui, 2004); a reduction in sediments results in a reduction in total P leaving the fields. Many previous studies have suggested a buffer width of 10 m (Castelle et al., 1994), while others have demonstrated an acceptable effect (50 – 80 percent) with 3 – 5 m wide buffers (e.g. Dillaha et al., 1989; Simmons et al., 1992). A relative mass loss of P in runoff was related to the width of buffer strip, according to first order equation (Figure 5-2). These findings reinforce recommendations from Overcash et al. (1981) regarding the use of first-order models for designing the width of vegetative buffer strips to remove pollutants from runoff. The present study also showed that a majority of losses in total P could be controlled by a 7.6 m wide buffer (50 – 75 percent), and doubling the buffer width to 15.2 m only marginally reduced total P losses further (Figure 5-2). A buffer strip width of 6.1 m produced reductions of up to 75 percent in TP from manure-applied soils (Lim et al., 1998) with no added benefit for wider buffer strips.

TABLE 5-4: EVOLUTION OF SOIL CONSERVATION SERVICE RECOMMENDATIONS FOR THE WIDTH OF GRASS BUFFER STRIPS

Standard Slope (%)	1988 (SCS, 1988) Minimum Width (m)	Standard Slope (%)	1990 (SCS, 1990) Minimum Width (m)	Standard Slope (%)	1997 (SCS, 1997) Minimum Width (m)
<1	3	0-5	6	0.5-5	11-22
0-10	5	5-6	9	≥5	36-71
		6-9	12		
10-20	6	9-13	15		

TABLE 5-5: MEAN PHOSPHOROUS CONCENTRATION IN RUNOFF AS A FUNCTION OF BUFFER STRIP WIDTH

Buffer	2008				2009			
	DMRP[1]		TP		DMRP		TP	
Width (m)	TSP	Biosolids	TSP	Biosolids	TSP	Biosolids	TSP	Biosolids
	---- mg L^{-1} ----							
---- Snowmelt Runoff -- ----								
0	0.21	0.23	0.58	1.05	0.31	0.37	0.44	0.62
7.6	0.22	0.24	0.50	0.55	0.28	0.33	0.37	0.55
15.2	0.25	0.25	0.45	0.51	0.27	0.30	0.32	0.52
---- Rainfall Runoff ----								
0	0.02	0.77	1.14	2.35	0.01	1.02	0.56	2.97
7.6	0.02	0.69	0.59	0.78	0.02	0.87	0.35	1.23
15.2	0.02	0.57	0.42	0.85	0.02	0.59	0.31	0.83
---- (Snowmelt + Rainfall) Runoff Volume – Weighted Mean----								
0	0.09	0.58	0.94	1.90	0.10	0.82	0.53	2.26
7.6	0.10	0.51	0.55	0.69	0.12	0.73	0.36	1.05
15.2	0.09	0.47	0.43	0.74	0.12	0.54	0.31	0.77

[1] Dissolved molybdate reactive P.

TABLE 5-6: ANNUAL RUNOFF LOSSES OF PHOSPHOROUS AS A FUNCTION OF BUFFER STRIP WIDTH

Buffer	2008				2009				Average of 2008 and 2009			
Width	DMRP[1]		TP		DMRP[1]		TP		DMRP[1]		TP	
(m)	TSP	Biosolids	TSP	Biosolids	TSP	Biosolids	TSP	Biosolids	TSP	Biosolids	TSP	Biosolids
	kg ha^{-1}											
	Snowmelt Runoff Losses											
0	0.47	0.45	1.27	2.10	0.66	0.70	0.93	1.18	0.56	0.58	1.10	1.64
7.6	0.45	0.45	0.99	1.05	0.56	0.33	0.74	0.55	0.51	0.39	0.87	0.80
15.2	0.37	0.27	0.67	0.56	0.44	0.18	0.52	0.31	0.40	0.23	0.59	0.44
	Rainfall Runoff Losses											
0	0.06	2.93	4.56	8.93	0.07	4.49	3.08	13.07	0.06	3.71	3.82	11.00
7.6	0.05	1.93	1.83	2.18	0.07	2.44	1.12	3.44	0.06	2.18	1.47	2.81
15.2	0.06	1.37	1.26	2.04	0.06	1.48	0.84	2.08	0.06	1.42	1.05	2.06
	Total Runoff Losses (Snowmelt + Rainfall)											
0	0.53	3.38	5.83	11.03	0.72	5.19	4.01	14.25	0.63	4.28	4.92	12.64
7.6	0.50	2.39	2.82	3.23	0.63	2.77	1.86	3.99	0.56	2.58	2.34	3.61
15.2	0.42	1.64	1.93	2.60	0.50	1.66	1.35	2.39	0.46	1.65	1.64	2.50

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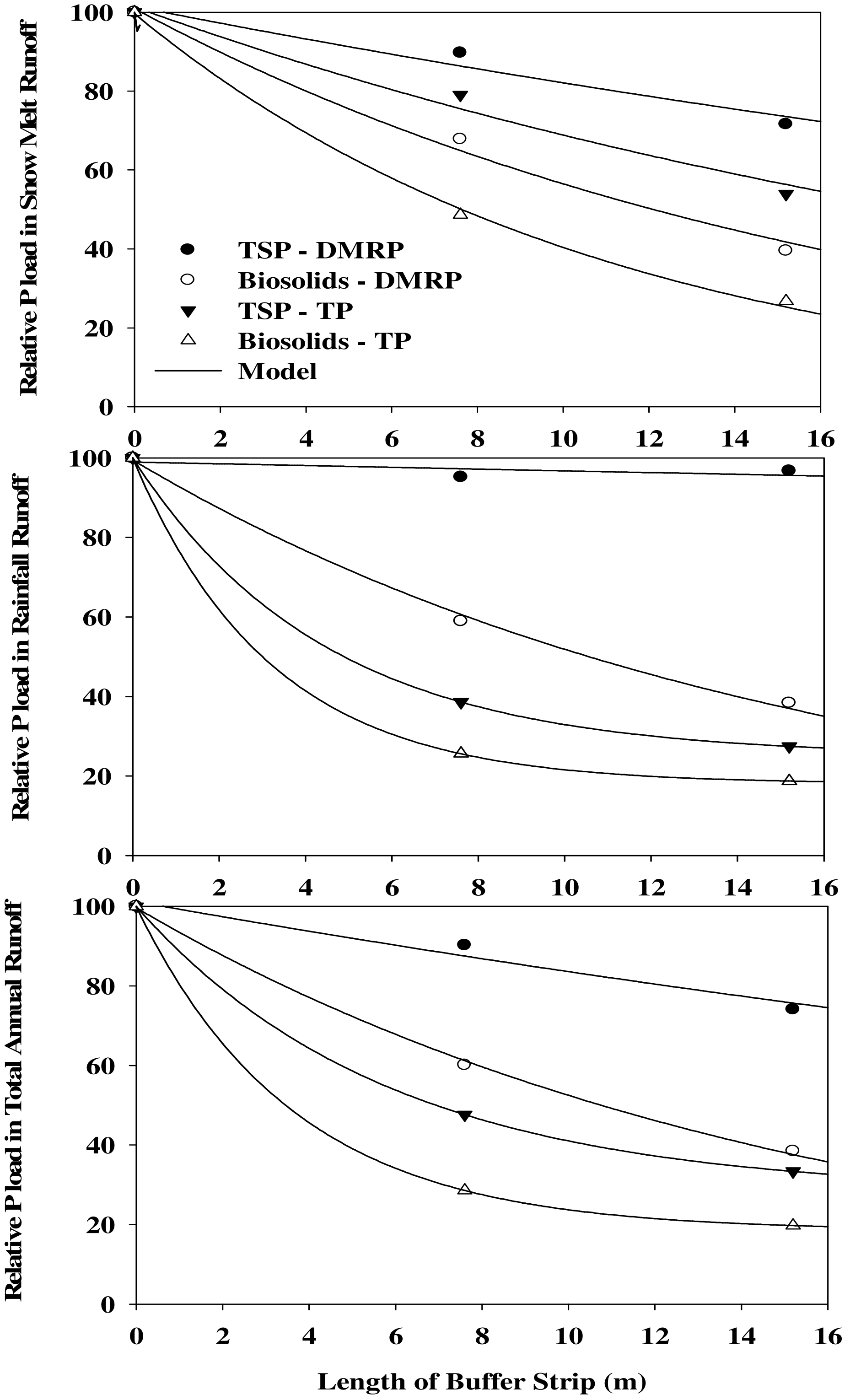
[1] Dissolved molybdate reactive P.

FIGURE 5-2: RELATIVE MASS OF TWO-YEAR AVERAGE DISSOLVED MOLYBDATE REACTIVE PHOSPORUS AND TOTAL PHSOPHORUS RUNOFF LOSSES AS AFFECTED BY TREATMENTS AND THE WIDTH OF BUFFER STRIP DURING SNOWMELT RUNOFF, RAINFALL RUNOFF, AND TOTAL ANNUAL RUNOFF



Conclusions

The results from this study are in agreement with the results from many published reports that a 5 to 10 m buffer width is sufficient to reduce both sediment and phosphorus losses from biosolids-applied soils. The federal regulation (40 CFR Part 503) for land application of biosolids (USEPA, 1993), requiring 10 m from surface waters and establishing grassy vegetation in this buffer zone, is sufficiently protective of surface water quality. The state of Illinois may also adopt these guidelines requiring 10 m grass buffered area from surface water for lands receiving biosolids at agronomic rates.

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