

**USE OF MUNICIPAL AND INDUSTRIAL WASTE AMENDMENTS  
TO REDUCE BIOAVAILABLE PHOSPHORUS  
FROM AGRICULTURAL LAND TREATED  
WITH ANIMAL MANURES**

By

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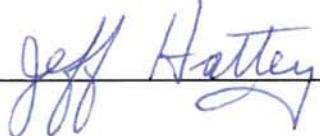
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## INTRODUCTION

Growing poultry and swine production has contributed to an increase in economic growth for Oklahoma agriculture. Along with economic benefits, producers are faced with disposal of large amounts of animal manure generated from poultry and swine production. Excessive land application of animal manure increases soil available P and has raised concerns about P runoff in eastern Oklahoma. The beneficial use of two drinking water treatment hydrosolids (alum sludges), cement kiln dust, and bauxite red mud to reduce bioavailable P in soils that contain excessive P from manure application was evaluated in this study. The potential environmental impact of aluminum, pH, salinity, and heavy metals on soil quality associated with land application of these waste materials was also determined.

This thesis consists of two manuscripts that will be submitted for publication in the *Journal of Environmental Quality*, an American Society of Agronomy publication.

## CHAPTER I.

### REDUCTION OF NON-POINT SOURCE PHOSPHORUS FROM AGRICULTURAL LAND USING NONHAZARDOUS WASTES

#### ABSTRACT

The beneficial use of two drinking water treatment hydrosolids (HS1, HS2), cement kiln dust (CKD), and bauxite red mud (RM) to reduce bioavailable P in soils that contain excessive P from manure application was evaluated. Two soils that contained 553 and 296 mg kg<sup>-1</sup> Mehlich III P from poultry or dairy manure were mixed with 100 g kg<sup>-1</sup> amendment and incubated at 25°C for 9 weeks. The ability of amendments to reduce bioavailable P and soluble P in soil was determined. Soil pH, salinity (EC), available aluminum, and heavy metal content and extractability were determined in amendments and soils to evaluate potential environmental impact. Reductions in bioavailable P from 490 mg kg<sup>-1</sup> to 250 mg kg<sup>-1</sup> followed the trend HS2, CKD > HS1 ≥ RM in the slightly acidic Dickson soils. Reductions in bioavailable P from 275 mg kg<sup>-1</sup> to 110 mg kg<sup>-1</sup> followed the trend HS2 ≥ HS1 > RM > CKD in the calcareous Keokuk soil. Reduction of soluble P by amendments followed similar trends. In general, increasing amendment rates from 30 to 100 g kg<sup>-1</sup> decreased bioavailable and soluble P. Most treatments did not result in excessive soil pH, increases in soil salinity, or extractable Al. Land application of hydrosolids used in this study

should not increase the content or availability of heavy metals in soils. Adverse potential environmental impacts from aluminum, pH, salinity, and heavy metals associated with application of amendments should be insignificant. Hydrosolid waste is currently being landfilled at great expense to municipalities. Hydrosolid application to soils in sensitive watersheds that have soils with excessive amounts of bioavailable P may improve drinking water quality, reduce drinking water treatment costs, and thus provide financial savings for municipalities.

## INTRODUCTION

Growing poultry and swine production has contributed to an increase in economic growth for Oklahoma agriculture (Sharpley et al., 1991). Along with economic benefits, producers are faced with disposal of large amounts of animal manure generated from poultry and swine production. Excessive land application of animal manure increases soil available P and has raised concerns about P runoff in eastern Oklahoma (Field et al., 1985; Reddy et al., 1980; Sharpley et al., 1991; Singh and Jones, 1976).

Recent benchmark Conservation Practice Standard and Waste Utilization guidelines passed by the Oklahoma Natural Resource Conservation Service (NRCS) limit animal manure applications to soils with excessive amounts of bioavailable P (NRCS, 1994). These guidelines were designed to determine application rates of animal manure beneficial to soils in sensitive watersheds. Application rates are based on soil bioavailable P determination by Mehlich III extraction, field slope, soil depth, soil erodibility, flood plain, and other factors that minimize non-point source pollution.

Recently, U.S. EPA Region VI promulgated Concentrated Animal Feeding Operation (CAFO) regulations and the Oklahoma Feed Yard Act adopted use of NRCS guidelines that limit application of animal manures to P sensitive watersheds. The NRCS guidelines limit animal manure applications to land with excessive amounts of available P.

Reduction of bioavailable P in soils that exceed CAFO levels would reduce the non-point source (NPS) threat to sensitive watersheds. In addition, land application of nonhazardous waste materials that reduce P solubility may be a feasible approach to reduce bioavailable P in soils.

Soluble forms of phosphorus are readily adsorbed and precipitated by soil or sediment components that contain aluminum, iron, and calcium (Hsu, 1964; Hsu, 1976). Iron and aluminum oxides (hydrated oxides) strongly adsorb and precipitate P from solution in natural water and soil systems (Stumm and Morgan, 1981; Tisdale et al., 1985). Calcium reacts with soluble P to form very insoluble phosphorus compounds (Lindsay, 1979).

Alum sludge, or hydrosolid, is a waste by-product generated from drinking water pretreatment. Hydrosolids contain aluminum oxides capable of adsorbing and precipitating soluble phosphorus. Hydrosolids as a soil amendment to improve the physical properties of potting media and plant growth have been investigated (Bugbee and Frink, 1985). Hydrosolids improved water holding capacity and acted as a liming material, but higher rates of hydrosolids caused severe P deficiency and decreased lettuce yield (Bugbee and Frink, 1985). Hydrosolid additions to soil improved soil structure and plant growth, but large application rates ( $>2 \text{ MT ha}^{-1}$ ) induced P deficiencies and reduced corn yields (Rengasamy et al., 1980). Land application of hydrosolids have induced similar P deficiencies in other studies (Heil and Barbarick, 1989). The ability of commercial alum to reduce soluble P in field runoff water has recently been reported (Moore and Miller, 1994). However, the chemical properties of commercial alum and

hydrosolids are very different. Alum (aluminum sulfate) is a very soluble salt that releases toxic aluminum and produces acidity when dissolved in water. Land application of alum may result in soil acidification and phytotoxic levels of  $Al^{3+}$ , which is not desirable. Hydrosolids are predominately insoluble aluminum oxides which are neutral to slightly alkaline. Hydrosolids should not release toxic aluminum or produce acidity in soil or aqueous systems.

Red mud contains large amounts of aluminum oxides, iron oxides, and calcium and is a waste product of the aluminum industry (Shiao and Akashi, 1977). Shannon and Verghese (1976) suggested that red mud could be economically used as an amendment for phosphorus removal by precipitation. After treatment with acids, red mud is an effective adsorbent for the removal of P (Barrow, 1982; Shiao and Akashi, 1977; and Weaver and Ritchie, 1987), however, red mud has undesirable properties. Red mud contains lye, has a high pH (9-12), large electrical conductivity (60-350 dS  $m^{-1}$ ), and large amounts of soluble sodium (9 meq  $100g^{-1}$ ) and aluminate. Land application of red mud results in saline and alkaline conditions and poor soil physical structure (Wong and Ho, 1991). Red mud is corrosive and is classified as a hazardous waste (Thompson, 1987). These undesirable properties have prevented use of red mud in natural water and soil systems (Vachon et al., 1994). Most studies have focused on reclamation of soils rendered infertile by red mud (Thompson, 1987). In a study by Vlahos et al. (1989) on the effects of P reduction on sandy soils, red mud was found to be an extremely effective material in removal of total P in leachate after application of superphosphate fertilizer. Water retention, pH, calcium, and total soluble salt increased after application of the red mud amendment to soil.

The ability of calcium to “fix” phosphorus into relatively insoluble forms is well known (Ford, 1933). Calcium reacts with soluble P to form insoluble calcium phosphates in soils at moderate to high pH (>6). Reagent-grade CaO and Ca(OH)<sub>2</sub> were found to be effective amendments in reducing soluble P in poultry litter (Moore and Miller, 1994). Cement kiln dust (CKD) is a waste product generated during production of cement. Cement kiln dust is rich in calcium and potassium oxides.

Land application of nonhazardous waste materials has the potential to reduce excessive amounts of bioavailable P in soil but information is needed. Waste materials that contain hydrous oxides (e.g., alum sludge, red mud) or calcium (cement kiln dust) are readily available. Information is needed to assess the ability of waste amendments to reduce bioavailable P and not cause any potential adverse environmental impacts. The beneficial use of two drinking water treatment hydrosolids, cement kiln dust, and bauxite red mud to reduce bioavailable P in soils that contain excessive P from excessive manure application was evaluated in this study. The potential environmental impact of aluminum, pH, salinity, and heavy metals on soil quality associated with land application of these waste materials was also determined.



## **MATERIALS AND METHODS**

### **Amendments**

Four amendments used in this study were a hydrosolid collected from Lake Wister, Oklahoma (HS1), a hydrosolid collected from Lake Oologah in Tulsa, Oklahoma (HS2), cement kiln dust from Blue Circle Cement in Tulsa, Oklahoma, and treated red mud from Alcoa in Point Comfort, Texas. Both hydrosolid materials were alum sludges. Untreated red mud contains lye and is considered hazardous waste because of its high corrosivity. The bauxite red mud was treated with gypsum and leached with deionized water to remove excess lye and sodium. This was accomplished by placing a mixture of 21 kg red mud with 4.1 kg gypsum in a 20.3 cm Carlon PS-115 PVC gravity sewer line pipe. A cap, with drainage holes and a nylon screen, was placed at the bottom of the column to prevent the loss of the red mud solid. Deionized water was leached through the column until the electrical conductivity (EC) was  $<2 \text{ dS m}^{-1}$ . A total of 64 L of deionized water was added over approximately 70 hours.

### **Amendment Properties and Chemical Characterization**

All amendments were analyzed for pH, salinity, calcium carbonate equivalent (CCE), total metal content, and extractable heavy metals by U.S. Environmental

Protection Agency Toxicity Characteristic Leaching Procedure (U.S. EPA, 1990) (Table 1).

Amendment pH was analyzed in 1:2 amendment:0.01 *M* CaCl<sub>2</sub> solution using a glass electrode (McLean, 1982). Electrical conductivity (EC), or salinity, of each amendment was analyzed in 1:2 amendment:deionized water solution (Rhoades, 1982). Calcium carbonate equivalent (CCE) was determined by placing 0.5 g of amendment in excess standard HCl and boiling for 5 minutes. CCE was determined by back-titration of remaining HCl with standard NaOH (Rund, 1984).

Total metal content of amendments was determined by wet digestion with HNO<sub>3</sub> and HClO<sub>4</sub>. Ten mL of HNO<sub>3</sub> was added to 2 g of each amendment in two replications. These samples were then placed into a heated digestion block for 2 hours at 150°C. After cooling, 10 mL of HClO<sub>4</sub> was added and heated for 1.5 hours at 215°C. Next, 4 mL of HCl was added and the mixture was heated for 0.5 hours at 120°C. Digested samples were diluted with deionized water to a final volume of 25 mL and filtered through 0.45 micron membrane filters. Acid digests were analyzed for Al, Ca, Cd, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, Pb, and Zn by inductively coupled plasma atomic emission spectroscopy (ICP).

Metals were extracted from amendments according to the U.S. EPA TCLP procedure (U.S. EPA, 1990). Pretreatment tests specified by this method showed HS1 and HS2 test solutions had pH <5.0 while CKD and RM test solutions had pH >5.0. Therefore, 0.2 *M* acetic acid, pH 5.0 (EF #1), was used for HS1 and HS2 and unbuffered 0.2 *M* acetic acid (EF #2) was used for CKD and RM. Amendment (2 g) was placed into

a 125 mL Erlenmeyer flask and 40 mL of the appropriate EF solution was added then placed on a shaker for 1 hour. The samples were filtered using 0.45  $\mu\text{m}$  membrane filters and analyzed by ICP instrumentation for Ba, Cd, Cu, Mo, Ni, Pb, and Zn.

### **Phosphorus Adsorption Index**

The ability of amendments to reduce soluble P was used as an index of their phosphorus adsorption capacity. A preliminary equilibration study, conducted to determine the shaking time needed to achieve equilibrium, showed equilibration was achieved after 15 hours and was used for all subsequent equilibrations. Amendments were equilibrated with 10, 25, 50, 100, 250, 500, 1000, 5000 and 10,000 mg P L<sup>-1</sup> standard solutions in three replications. The samples were then centrifuged and analyzed using the modified Murphy-Riley method (Murphy and Riley, 1962).

### **Soil Properties**

Three soils that received large amounts of animal manures and contained large amounts of Mehlich III (Mehlich, 1984) available P were selected for the incubation study (Table 2). Mehlich III available P was 553, 510 and 296 mg P kg<sup>-1</sup> and soil pH was 5.3, 5.8, and 8.2 for Dickson silt loam #1 (fine-silty, siliceous, Thermic Glossic Fragiudult), Dickson silt loam #2, and Keokuk very fine sandy loam (coarse-silty, mixed, Thermic Fluventic Haplustoll), respectively. The Dickson soils were from Adair county, Oklahoma and received >10 years of poultry litter. The Keokuk soil was from Grady county, Oklahoma and received >10 years of dairy manure.

Cation exchange capacity of the soils was determined by using  $\text{BaCl}_2$  as described by Rhodes (1982). Citrate-bicarbonate-dithionite procedure described by Olsen and Ellis (1982) was used to measure free iron oxides. The modified Mebius method was used to determine the soil organic carbon content of each soil (Yeomans and Bremner, 1988).

### **Incubation Study**

Soils were incubated with amendments to evaluate reductions in bioavailable P during the incubation period. Three different soils (two Dickson soils and a Keokuk soil) were analyzed after 3, 5, and 9 weeks of incubation for soil pH, EC, Mehlich III P, soluble P, and total aluminum.

The incubator temperature was  $26^\circ\text{C}$  during the day (16 h) and  $24^\circ\text{C}$  during the night (8 h). The incubator was maintained at approximately 60% humidity. Soil (250 g) was mixed with amendment rates of  $30 \text{ g kg}^{-1}$  and  $100 \text{ g kg}^{-1}$  in plastic pots. Soils were maintained at field capacity (-0.3 bar) moisture content. A preliminary study with 10, 50, 100, and  $200 \text{ g kg}^{-1}$  amendment rates suggested  $30 \text{ g kg}^{-1}$  and  $100 \text{ g kg}^{-1}$  rates were needed to reduce bioavailable P. The experimental design was a completely randomized design with three replications and controls (no amendment added) for each soil. Three soils with an initial Mehlich III P of 553, 466, and  $310 \text{ mg P kg}^{-1}$  were chosen due to their high bioavailable P levels and initial pH. Triumph 64 wheat (*Triticum spp.*) was planted on the amended soils as a qualitative indicator of amendments on crop growth.

## Soil Analysis

Soil pH and EC were analyzed as described in the Amendment Properties and Chemical Characterization section. Soil pH was determined after 3 and 9 weeks of incubation and EC was only measured after 9 weeks of incubation.

The ability of amendments to reduce bioavailable P was determined by measuring phosphorus extracted by the Mehlich III procedure from amended soils at 3, 5, and 9 weeks of incubation (Mehlich, 1984). Twenty mL of Mehlich III extractant was added to 2 g of soil from each sample and placed on a rotary shaker for 5 minutes. The samples were then filtered using Whatman #2 filter paper (McElreath and Johnson, 1990). The filtrate was then diluted to a 1:10 filtrate to deionized water solution. A 0.25 mL aliquot was pipetted into a 20 mL test tube and 5 mL of deionized water was added followed by 1 mL of Reagent B (Murphy and Riley, 1962). After 10 minutes of color development, sample absorbance at 882 nm was measured.

Soluble P in amended soils was determined after 9 weeks of incubation. Ten mL of 0.01 M CaCl<sub>2</sub> was added to soil (5 g) and placed on a shaker for 15 h. The Modified Murphy-Riley method was used to analyze soluble P in filtered soil solution.

Extractable aluminum was determined using potassium chloride (KCl) extraction (Barnhisel and Bertsch, 1982). The soils (2.5 g) subjected to incubation from the 9 week sampling time was mixed with 25 mL of 1 N KCl and shaken for 30 minutes. Soil mixtures were centrifuged at 2,900 g for 3 minutes and filtered through 0.45 micron membrane filter paper. Aluminum in KCl extract was measured by ICP instrumentation.

## RESULTS AND DISCUSSION

Batch equilibration of amendments with standard solutions for 15 h containing P showed all four amendments adsorb soluble P. All four amendments sorbed greater than 90% of P from solutions with initial concentrations  $<500 \text{ mg P L}^{-1}$  (Fig. 1). Amendments sorbed between 45% to 90% of dissolved P from solutions with initial concentrations  $>500 \text{ mg P L}^{-1}$ . In general, the ability to reduce soluble P was greater for CKD and HS2 than HS1 and RM.

The ability of the amendments to reduce bioavailable and soluble P in soil was determined by an incubation study with the three soils and four amendments. A preliminary two week incubation study showed reduction of Mehlich III (M3) P with amendment rate was approximately linear (Fig. 2). All amendment rates reduced M3 P, but the  $200 \text{ g kg}^{-1}$  rate, which represented  $134 \text{ MT ha}^{-1}$  incorporated into a 5 cm depth, was considered agronomically excessive. Therefore, 30 and  $100 \text{ g kg}^{-1}$  rates were selected for incubation under controlled environmental conditions.

### Reduction in Bioavailable P

The greatest changes in M3 P and pH occurred in the first three weeks of incubation for the Dickson soil #1 (Fig. 3). Chemical reactions between the soils and

amendments were assumed to be essentially complete after nine weeks of incubation. Similar results were found for the Dickson #2 and Keokuk soils. Therefore, only results obtained after nine weeks of incubation will be presented in the following discussion.

All three soils showed significant ( $P < 0.05$ ) decreases in M3 P for all amendment treatments after nine weeks of incubation (Fig. 4). Reduction of M3 P followed the trend HS2, CKD > HS1  $\geq$  RM for both slightly acidic Dickson soils. A different trend for the calcareous Keokuk soil was found: HS2  $\geq$  HS1 > RM > CKD. The hydrosolids followed the same general trend in both slightly acidic and calcareous soils: HS2  $\geq$  HS1. Hydrosolids contain large amounts of freshly precipitated aluminum oxides (Elliott et al., 1988). These amorphous Al oxides are highly reactive and adsorb large amounts of P from solution (Elliott et al., 1988; Young et al., 1988). Amorphous Al oxides in the hydrosolids used in this study adsorbed bioavailable P in the treated soils. Because drinking water treatment may involve adjustment of water pH with liming materials, some hydrosolids can contain significant amounts of calcium. Hydrosolid additions to soil may reduce phosphorus solubility and bioavailability by forming calcium phosphate precipitates. The larger total Ca in HS2 compared to HS1 (Table 3) suggests larger reductions in M3 P may be due to formation of Ca precipitates. The ability of CKD to reduce P in the calcareous soil is significantly less than P reductions in slightly acidic soils. Although CKD does not contain large amounts of aluminum oxides it does contain significant amounts of Ca (Table 3). Large amounts of Ca in CKD may reduce P bioavailability in soil by forming P precipitates. Reductions of M3 P from CKD treatments were greater in the slightly acidic Dickson soil than in the calcareous Keokuk

soil (Fig. 4). These differences may be related to relative contribution of CKD to the soluble Ca content of the treated soils. Because calcareous soils contain free  $\text{CaCO}_3$  and soil solution is often saturated with soluble Ca, the CKD treatment had less impact on the soluble Ca in the calcareous soil than the Dickson soils. Treatment of soil with CKD probably resulted in formation of more Ca-P precipitates in the Dickson soils than in the Keokuk soil. In general, increasing amendment rates from 30 to 100  $\text{g kg}^{-1}$  decreased soil M3 P.

Other studies have reported hydrosolid addition to soil induced P plant deficiencies (Elliott et al., 1988; Elliott et al., 1990; Heil and Barbarick, 1989; Young et al., 1988) which decreases plant yields. Heil and Barbarick (1989) found sorghum-sudangrass yield decreased after hydrosolid addition and they attributed the decrease to P fixation. Elliott et al. (1988) and Young et al. (1988) suggested decreased available P was due to the Al hydrous oxides, which have extremely high surface areas and are quite reactive as P sorbing surfaces. Bugbee and Frink (1985) found lettuce turned a purple hue after application of a hydrosolid due to an induced P deficiency. Elliott and Singer (1988) noted a decrease in yield from P deficiency in tomato shoots. Elliott et al. (1988) recommended adding P fertilizer to offset losses of available P in soils amended with hydrosolids.

Recently, Conservation Practice Standard and Waste Utilization guidelines have been passed by the Oklahoma Natural Resource Conservation Service (NRCS) that limit application of animal manures to soils with excessive amounts of bioavailable P (NRCS, 1994). These bioavailable P guidelines, determined by M3 P in soil, are used to determine



if a soil contains excessive amounts of P. These standards may be used to comply with U.S. EPA Concentrated Animal Feeding Operations regulations in Region VI (Smolen and Caldwell, 1994). NRCS guidelines consider soil with M3 P  $>200 \text{ mg kg}^{-1}$  as a severe non-point source threat of P pollution. Although none of the amendments reduced M3 P  $<200 \text{ mg kg}^{-1}$  in this study, the HS2  $100 \text{ g kg}^{-1}$  rate lowered the M3 P from 554 to  $247 \text{ mg kg}^{-1}$  in the Dickson soils. In the Keokuk soil, the HS1, HS2, and RM  $100 \text{ g kg}^{-1}$  rate lowered the M3 P from 296 to  $<200 \text{ mg kg}^{-1}$ . The addition of these amendments may decrease the non-point source (NPS) runoff threat from phosphorus to sensitive surface waters.

Most forms of soluble P are immediately available for uptake by aquatic life. However, the M3 P procedure extracts both readily soluble and insoluble P minerals that may not be immediately bioavailable in aquatic environments (Fixen and Grove, 1990). Although M3 P is related to potential P availability and NRCS guidelines are based on M3 P, soluble P may be a better environmental indicator of impact on aquatic life. Readily soluble P, extracted by using 1:2 soil:0.01 M  $\text{CaCl}_2$ , was also determined in treated soils. All amendments reduced soluble P in soils (Fig. 5). Reduction of soluble P in Dickson and Keokuk soils followed the trend  $\text{HS2} \geq \text{HS1} > \text{CKD}, \text{RM}$ . Soluble P reduction is similar to M3 P reduction results (Fig. 4) where P is adsorbed and precipitated by aluminum oxides and/or Ca in the amendments. A greater reduction in soluble P was found in the slightly acidic Dickson soils than in the calcareous Keokuk soil (Fig. 5). Similar to M3 P reduction, increasing the amendment rates from 30 to  $100 \text{ g kg}^{-1}$  reduced soluble P in all treatments except for HS2 in the Keokuk soil.

### Potential Environmental Impact

Soil pH, salinity (EC), extractable aluminum and heavy metal content and extractability were determined in amendments and soils to ensure the addition of amendments to soil did not result in undesirable environmental impacts. During the incubation study, Triumph 64 wheat (*Triticum spp.*) was planted in the treated soils as a qualitative indicator for nutrient induced deficiencies. Visual indications of nutrient deficiencies did not occur.

The slightly acidic Dickson soils showed significant increases in pH from 5.7 to 8.0 after the addition of CKD at the 100 g kg<sup>-1</sup> rate (Fig. 6). Cement kiln dust, a known liming material, can easily increase soil pH >7.0 (Gelderman et al., 1992). In general, increasing the amendment rate from 30 to 100 g kg<sup>-1</sup> significantly increased pH for all amendments in the Dickson soil. In the Keokuk soil, slight but significant (P < 0.05) increases in pH were found for all amendment rates. A final pH <8.3 for all the treated soils is not considered excessive and is not typically associated with environmental hazards.

Several amendments (CKD, RM) have significant amounts of soluble salts (Table 1). Soluble components of amendments might increase soil salinity. The impact of amendments on soil salinity was determined by measuring the electrical conductivity (EC) of treated soils. All rates of hydrosolids or 30 g kg<sup>-1</sup> rates of CKD or RM did not increase soil salinity (Fig. 7). However, 100 g kg<sup>-1</sup> rates of CKD and RM resulted in small but significant (P < 0.05) changes in EC. Salinity levels from 100 g kg<sup>-1</sup> rates of CKD and

RM may affect salt sensitive plants (Rhoades and Miyamoto, 1990). Soil salinity from other rates and amendments should have no effect on plant yield.

Commercial alum has a high water solubility and releases large amounts of phytotoxic aluminum in aqueous systems. Land application of alum may lead to aluminum phytotoxicity and is not recommended. Hydrosolids are derived from alum but consist of insoluble Al hydroxides and polymers (Bugbee and Frink, 1985). The effect of hydrosolids and other amendments on extractable aluminum in soil was measured after incubation (Fig. 8). In Dickson soil #1, the 100 g kg<sup>-1</sup> rate of HS2 showed a significant increase in extractable Al from the control. In Dickson soil #2, the 30 g kg<sup>-1</sup> rate of RM showed a significant increase in extractable Al from the control. All other amendments in the Dickson soils were not significantly different ( $P < 0.05$ ). In the Keokuk soil, only the 100 g kg<sup>-1</sup> rate of HS1 showed a significant increase in extractable Al from the control. Amendments did not increase extractable aluminum in incubated soils  $>5$  mg Al kg<sup>-1</sup>. Adverse affects are associated with much higher levels of extractable Al ( $>60$  mg kg<sup>-1</sup>) for wheat (Sloan et al., 1995). Therefore, slight increases in available aluminum from application of amendments should not have adverse effects on soils or plants.

Because excessive amounts of heavy metals in soils can result in agroecosystem pollution and contamination of the food chain, the effect of land application of hydrosolids on heavy metal content of soil was considered. Although the heavy metal content of most hydrosolids is similar to soil, several types of hydrosolids have been shown to contain elevated levels of trace and heavy metals (Elliott et al., 1990). Heavy metals in most hydrosolids originate from ferric coagulant chemicals produced as by-products of other

processes. Ferric coagulant wastes from steel pickling or associated with bauxite extractions may result in hydrosolids that contain elevated levels of  $307 \text{ mg kg}^{-1}$  Ni (Elliott et al., 1990; Heil and Barbarick, 1989). Heil and Barbarick (1989) found application of an acidic hydrosolid (pH 5.1) to an acid soil (pH 5.2) resulted in forages that contained  $>2 \text{ mg Cd kg}^{-1}$  which may pose a threat to livestock (NRC, 1980). They recommended liming of acid soil to pH  $>6.0$  before land application of acidic hydrosolids to minimize Cd availability and plant uptake. Most studies show that heavy metal associated with land application of water treatment sludges is insignificant and does not pose any environmental threat (Elliott et al., 1990; Heil and Barbarick, 1989).

Total content and TCLP extractable metals of amendments were determined to evaluate potential environmental threats associated with land application of amendments used in our study (Table 3). With the exception of total Cd in CKD and total Cd and Pb in RM, all amendment total metal contents were within the range of a typical soil total metal contents. Therefore, land application of these materials will not likely increase heavy metal concentrations in soil. Heavy metals extracted by TCLP were below U.S. EPA regulatory levels providing evidence that the amendments are not hazardous wastes. The U.S. EPA extraction procedure is used to classify wastes materials but may also provide information on bioavailable forms of heavy metals. Dilute acetic acid, the TCLP extractant, determines forms of metals that are bioavailable in soil. Therefore, heavy metals measured by TCLP should be a better indicator of potential environmental impact than total metal content (Scott, 1994). Comparison of TCLP and total metal values show most heavy metal is not in bioavailable forms (Table 3). Amendment TCLP levels were

similar to metal concentrations determined by TCLP in typical soils (Scott, 1994). Therefore, land application of hydrosolids should not increase heavy metal availability in soil. Similarly, Elliott et al. (1990) found most heavy metals in hydrosolids were strongly bound by aluminum and iron oxides in forms that do not have potential adverse environmental impacts.

## SUMMARY

The addition of hydrosolids, cement kiln dust, and bauxite red mud are beneficial in reducing the potential environmental impact from NPS runoff of bioavailable P. Increasing the rate of amendment will, in most cases, increase the amount of bioavailable P reduction. Potential adverse environmental impacts from application of these municipal and industrial amendments should be insignificant. Most soil treatments did not result in excessive soil pH or increase soil salinity. Hydrosolid applications had little or no effect on extractable Al in soil. Land application of hydrosolids used in this study should not likely increase the content or availability of heavy metals in soils. However, high rates of cement kiln dust and bauxite red mud may increase soil salinity in the amended soil, which may affect salt sensitive crops. Hydrosolid wastes are currently being landfilled at great expense to municipalities. Also, several municipal water treatment plants producing hydrosolids in Oklahoma may have source water degraded by non-point source P pollution. Hydrosolid application to soils in sensitive watersheds that have soils with excessive amounts of bioavailable P may improve drinking water quality and provide financial savings for municipalities.

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Table 1. Chemical Properties of Amendments Added to Soils

Amendment	pH <sup>†</sup>	EC <sup>‡</sup>	CCE <sup>§</sup>	Total Al	Total Fe
				----- g kg <sup>-1</sup> -----	
HS1	7.0	0.31	1.87	141	35.8
HS2	7.6	0.58	14.8	147	29.6
CKD	12.6	17.8	87.5	17.6	-
RM	8.1	2.63	24.2	111	209

<sup>†</sup> pH measured in 1:2 amendment:0.01 M CaCl<sub>2</sub>

<sup>‡</sup> Electrical conductivity (dS m<sup>-1</sup>)

<sup>§</sup> Calcium carbonate equivalent expressed in percent

Table 2. Soil Chemical Properties and Characteristics

Soil Series	Soil pH	Soil Texture	Initial Mehlich III mg kg <sup>-1</sup>	CEC† cmol <sub>c</sub> kg <sup>-1</sup>	Fe <sub>2</sub> O <sub>3</sub> ‡ g kg <sup>-1</sup>	OC§ g kg <sup>-1</sup>
Dickson #1	5.3	silt loam	553	9.3	0.15	17.2
Dickson #2	5.7	silt loam	510	12.9	0.14	35.0
Keokuk	8.0	sandy loam	296	13.7	0.10	13.1

† Cation exchange capacity

‡ Free iron oxides - expressed as Fe

§ Soil organic carbon content

Table 3. Extractable TCLP and Total Metal Contents of Amendments Added to Soils

	Amendments <sup>†</sup>				Normal range in soils <sup>‡</sup>
	HS1	HS2	CKD	RM	
<b>Total Metal</b>	----- mg kg <sup>-1</sup> -----				
Cd	0.57	0.93	2.98	6.61	0.01 - 1.3
Cu	24.8	37.9	7.48	27.3	1.4 - 216
Mo	0.12	0.25	0.70	0.53	0 - 40
Ni	26.6	28.5	14.4	10.0	2.2 - 154
Pb	14.0	15.9	29.7	56.4	3.0 - 36
Zn	86.1	80.7	36.8	56.1	3.2 - 170
	----- g kg <sup>-1</sup> -----				
Al	141	147	17.6	111	11 - 79
Ca	2.1	21.9	205	65.0	1 - 18
Fe	35.8	29.6	-	209	0.7 - 56
K	0.79	1.2	-	-	0.8 - 33
Mg	3.26	7.2	7.2	0.79	0.6 - 12
Mn	11.0	0.82	0.13	0.03	0 - 4
Na	0.09	0.38	1.65	9.25	0.7 - 22
	----- EPA Regulatory Limit <sup>§</sup> -----				
<b>TCLP<sup>¶</sup></b>	----- mg L <sup>-1</sup> -----				
Ba	1.17	0.83	0.20	0.02	100
Cd	0.03	0.03	0.03	0.03	1.0
Cu	0.03	0.02	0.03	0.03	-
Mo	0.06	0.05	0.08	0.03	-
Ni	0.06	0.03	0.08	0.40	-
Pb	0.08	0.08	0.16	0.16	5.0
Zn	0.07	0.08	0.13	0.40	-

<sup>†</sup> HS1 = hydrosolid from Lake Wister, Oklahoma; HS2 = hydrosolid from Lake Oologah, Oklahoma; CKD = cement kiln dust from Tulsa, Oklahoma; and RM = bauxite red mud from Point Comfort, Texas.

<sup>‡</sup> Cd, Cu, Ni, Pb, Zn, from Holmgren et al. 1993 (1st to 99th percentile); Mo from Alloway, 1990; Al, Ca, Fe, K, Mg, Mn, Na from Isaac and Kerber, 1971.

<sup>§</sup> Regulatory limit specified by U.S. EPA SW-846 Method 1311.

<sup>¶</sup> TCLP = Toxicity Characteristic Leaching Procedure, U.S. EPA Method 1311.

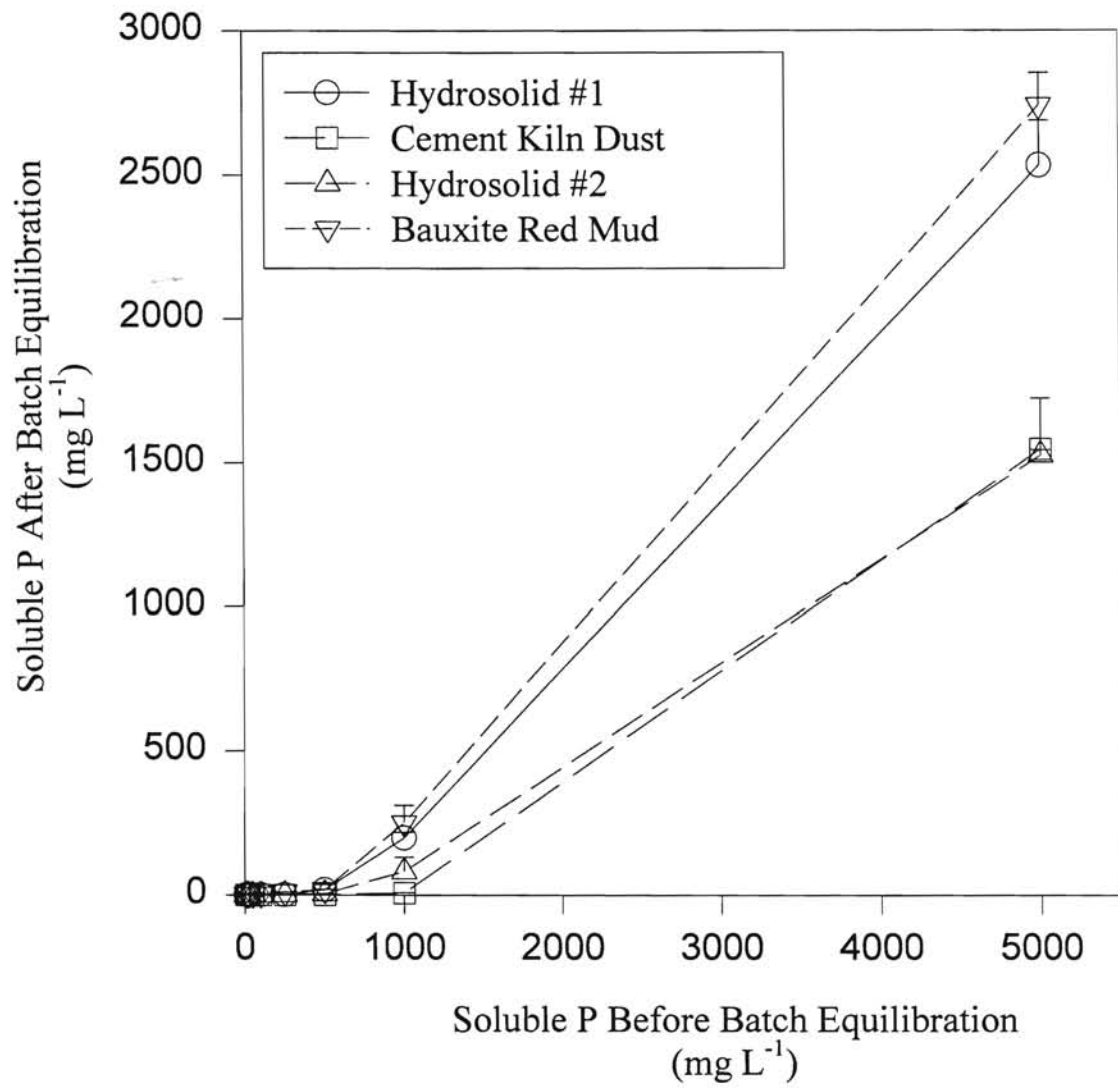


Figure 1. Dissolved P reduction from amendments

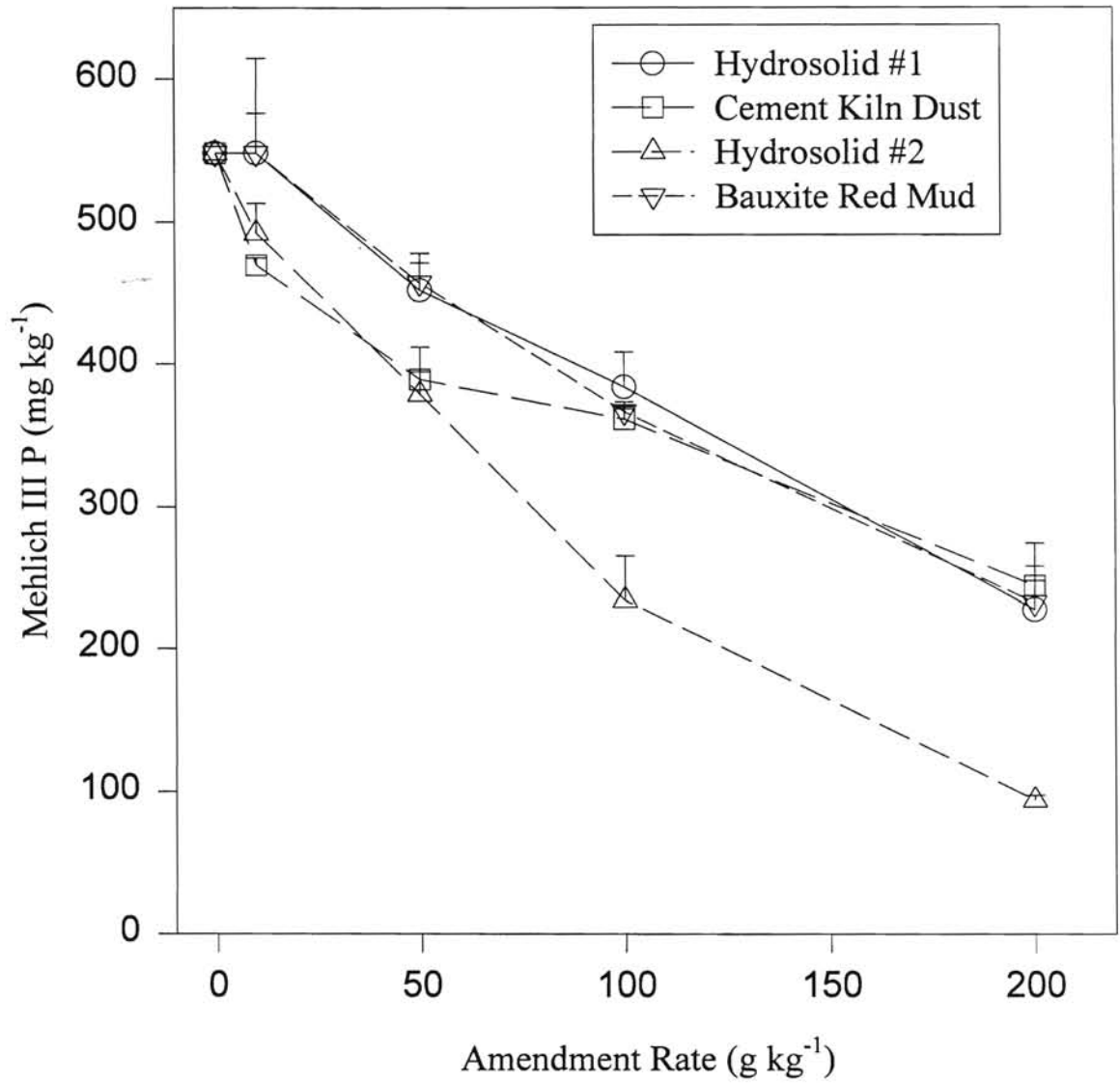


Figure 2. Mehlich III P response to amendment rate in the Dickson #1 soil.

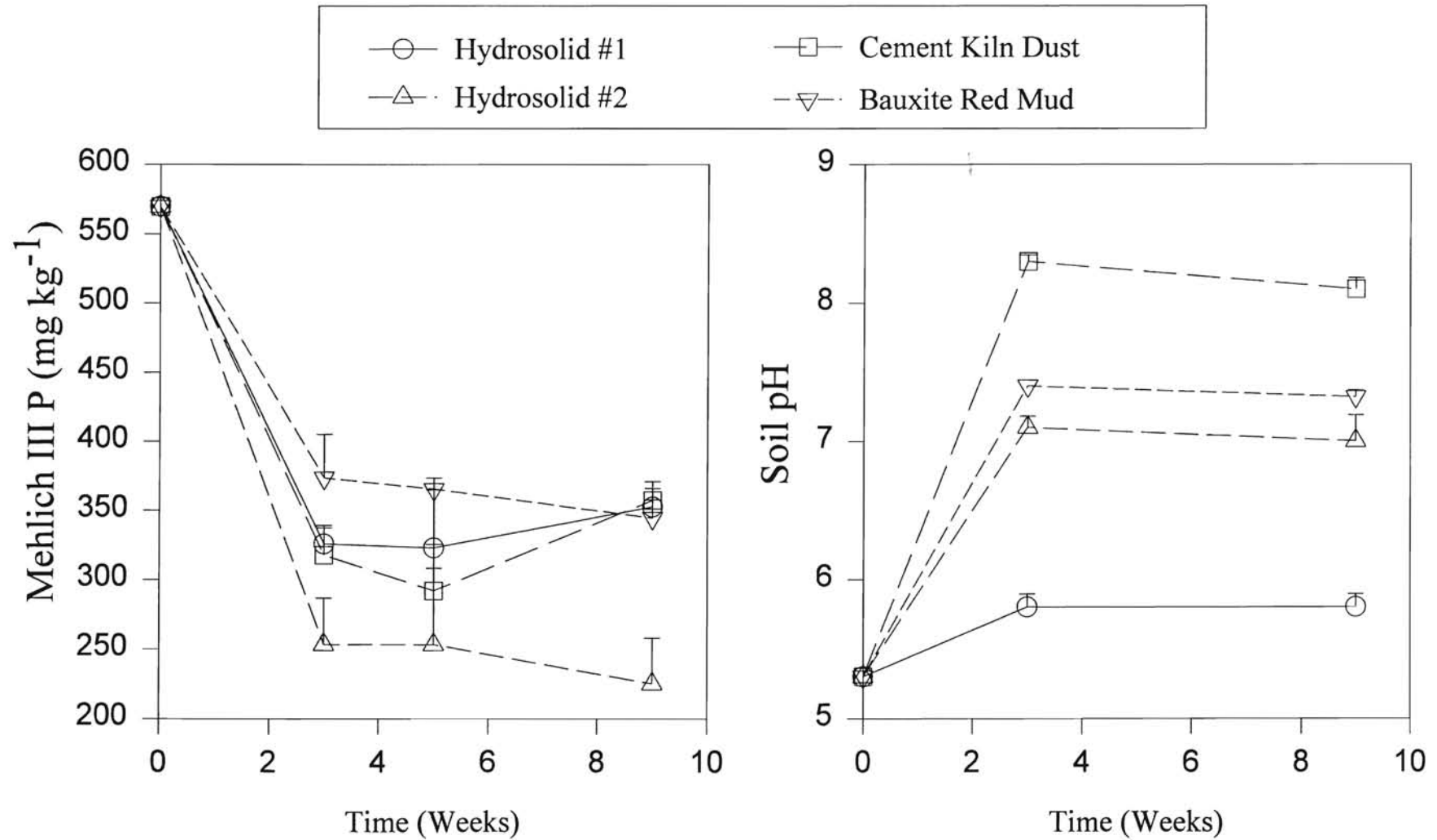


Figure 3. Response of Mehlich III P and soil pH treatment means to amendment ( $100 \text{ g kg}^{-1}$ ) with time for the Dickson soil #1.



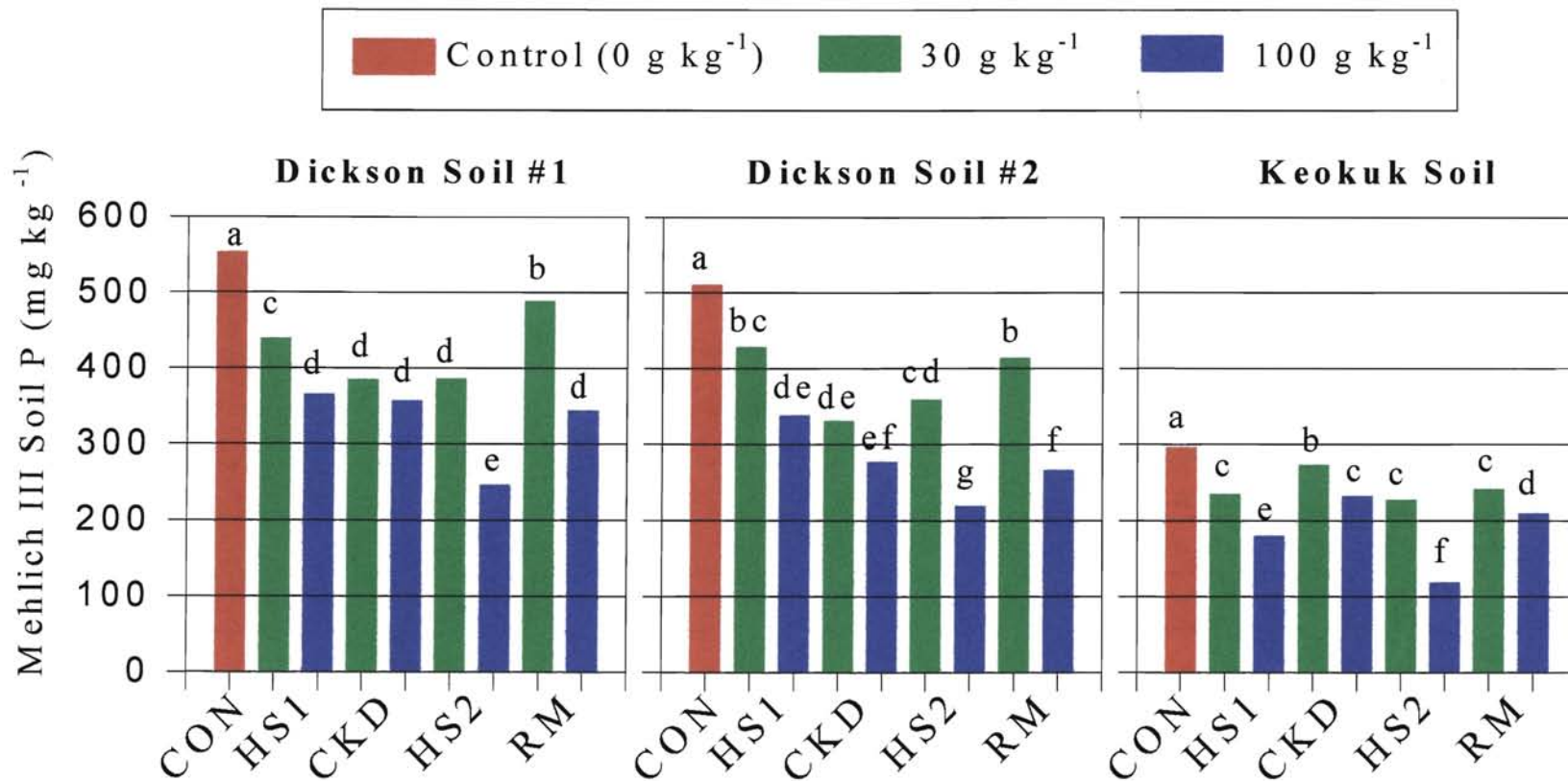


Figure 4. Mehlich III P in amended soils after 9 weeks of incubation. Columns with the same letter are not different at  $P < 0.05$  within a soil. CON = control; HS1 = hydrosolid #1; CKD = cement kiln dust; HS2 = hydrosolid #2; RM = bauxite red mud.

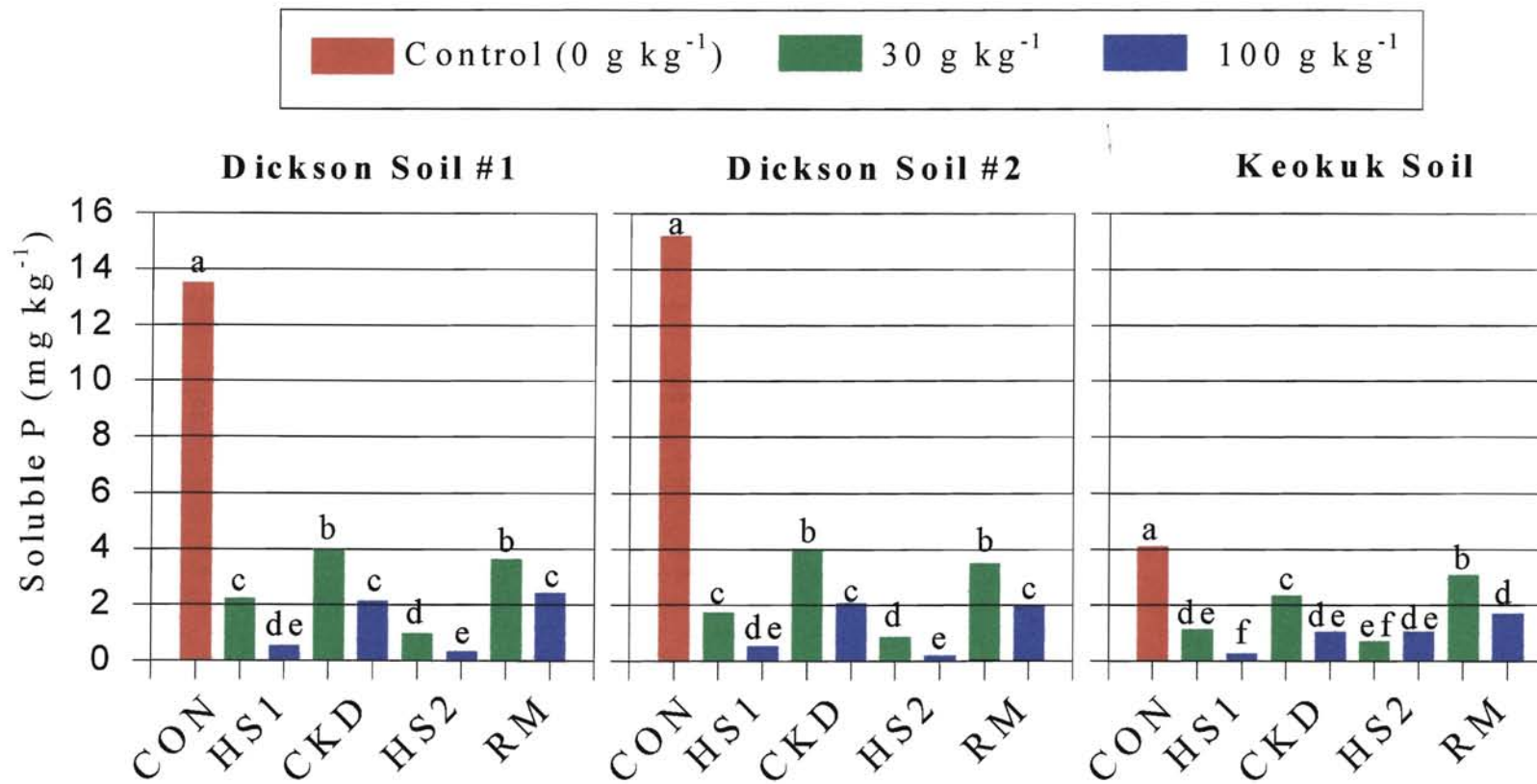


Figure 5. Soluble P in amended soils after 9 weeks of incubation. Columns with the same letter are not different at  $P < 0.05$  within a soil. CON = control; HS1 = hydrosolid #1; CKD = cement kiln dust; HS2 = hydrosolid #2; RM = bauxite red mud.

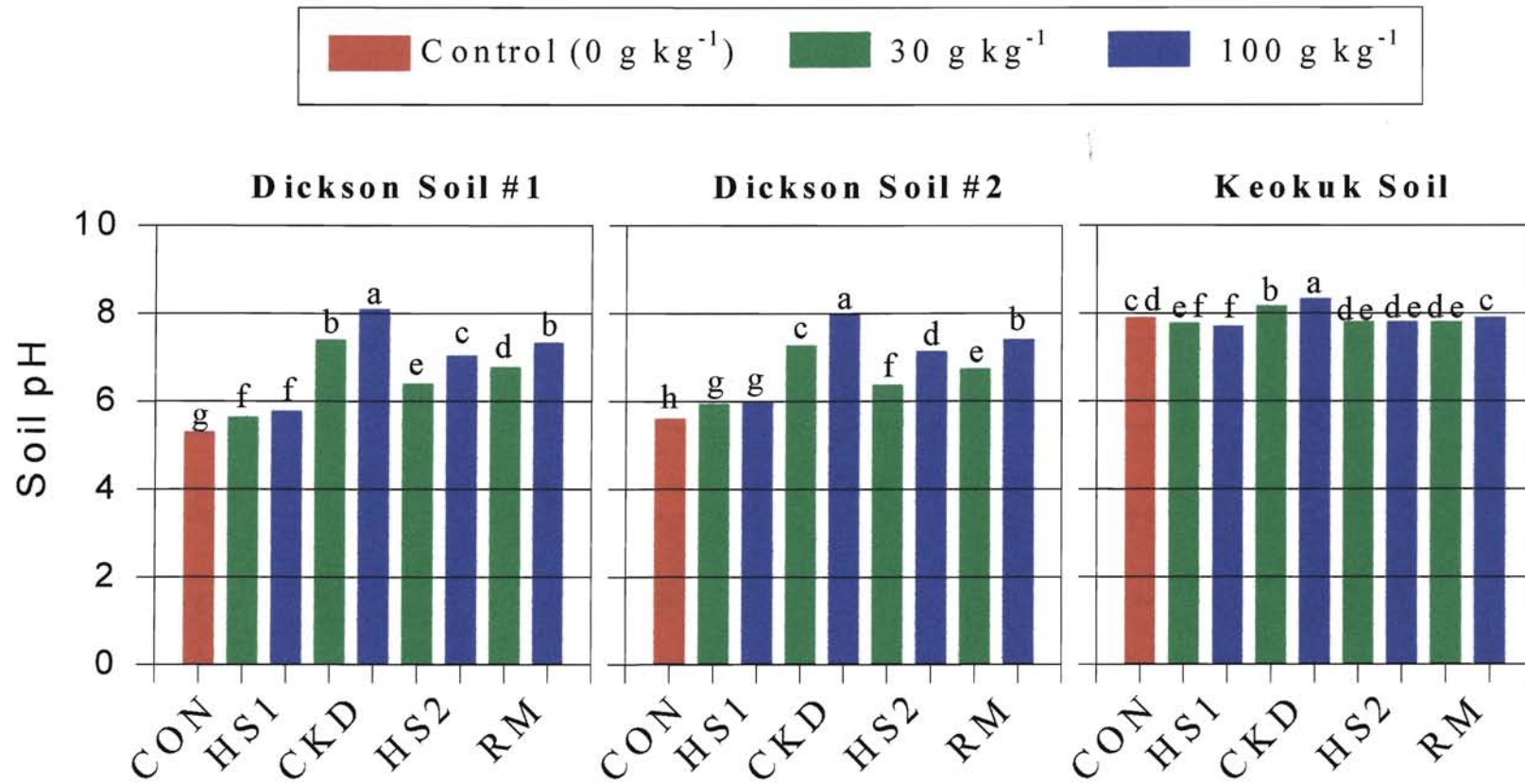


Figure 6. Effects of amendments on soil pH after 9 weeks of incubation. Columns with the same letter are not different at  $P < 0.05$  within a soil. CON = control; HS1 = hydrosolid #1; CKD = cement kiln dust; HS2 = hydrosolid #2; RM = bauxite red mud.

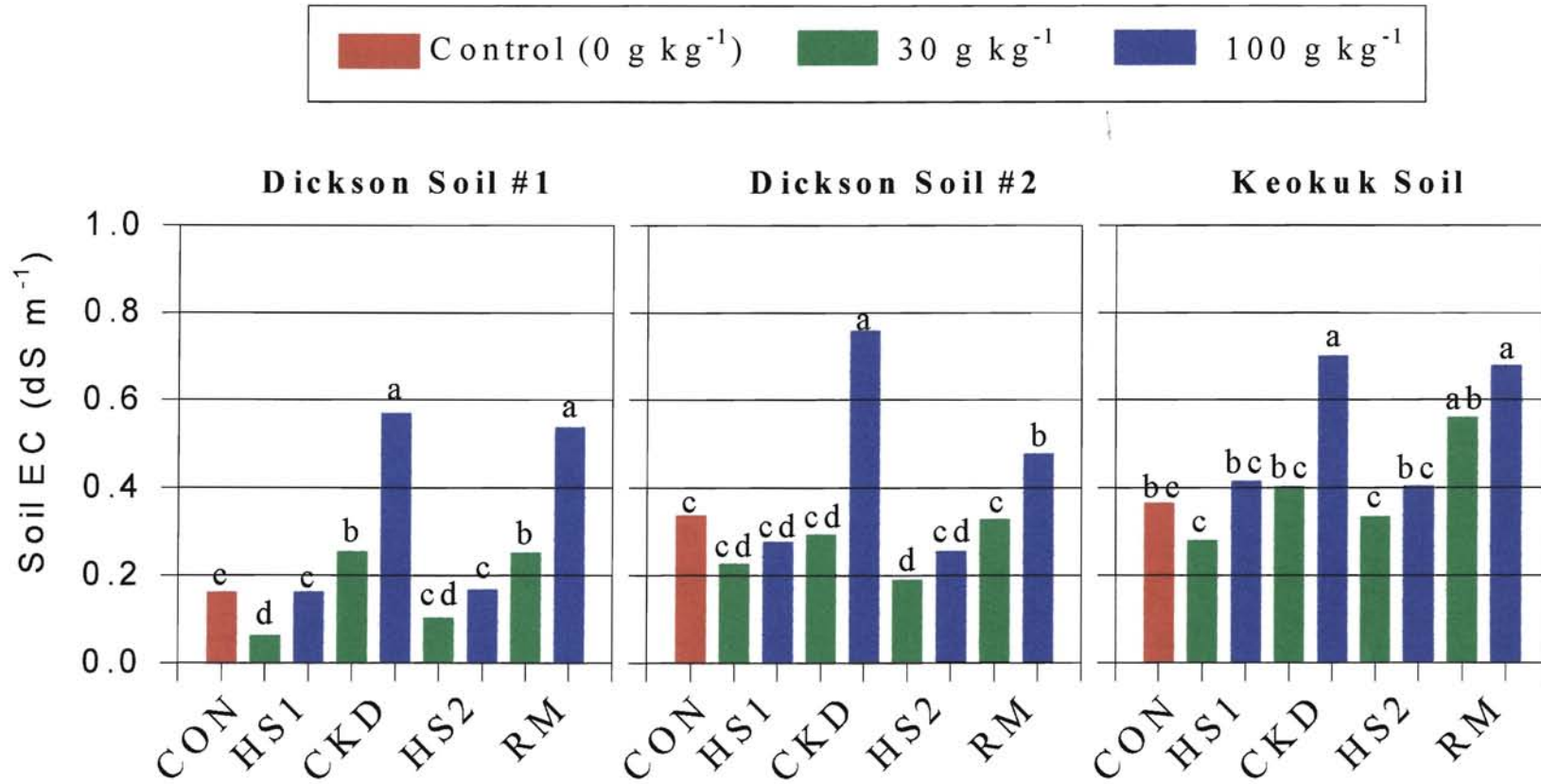


Figure 7. Effects of amendments on soil salinity after 9 weeks of incubation. Columns with the same letter are not different at  $P < 0.05$  within a soil. CON = control; HS1 = hydrosolid #1; CKD = cement kiln dust; HS2 = hydrosolid #2; RM = bauxite red mud.

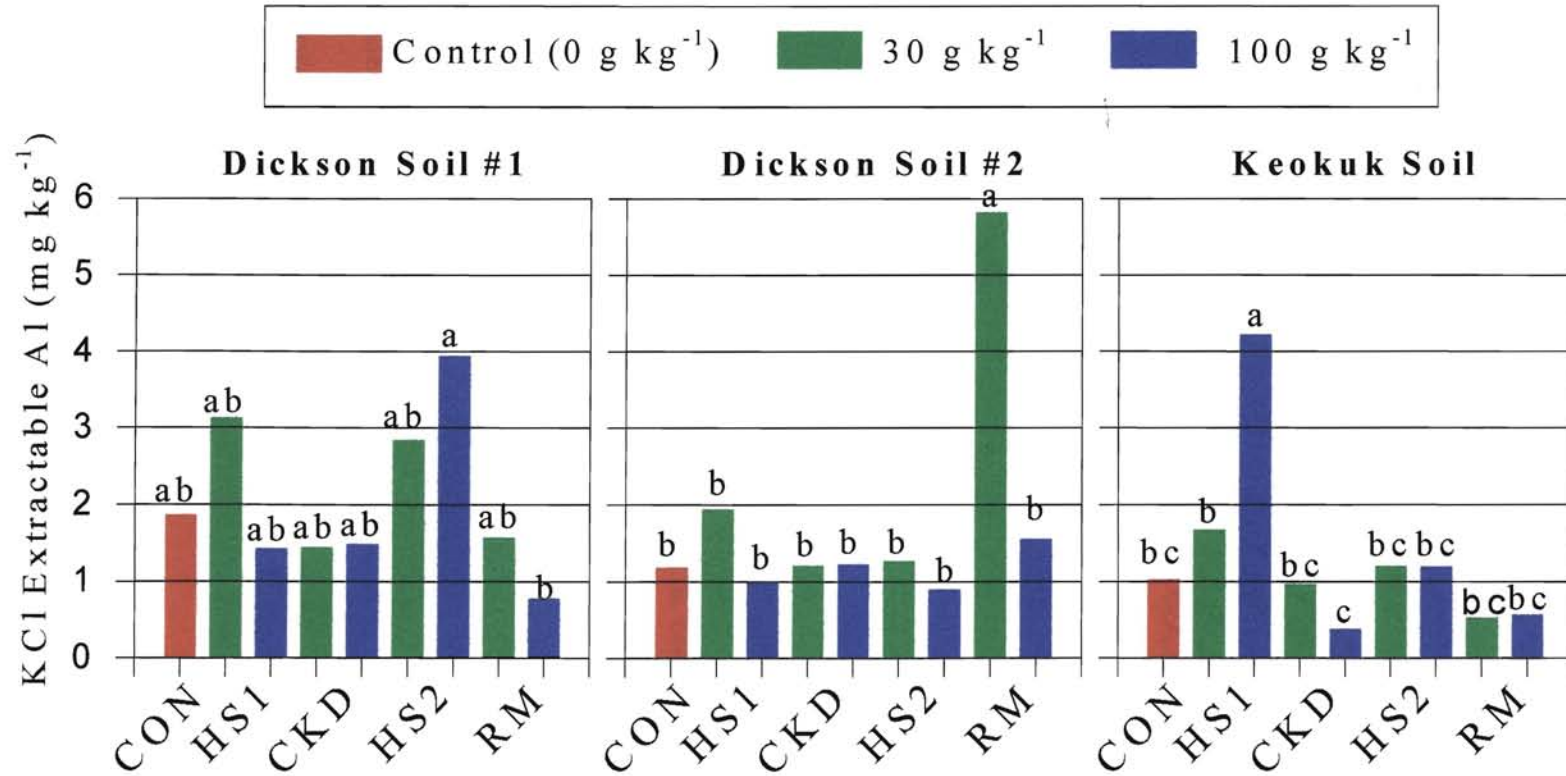


Figure 8. Effects of amendments on KCl extractable aluminum after 9 weeks of incubation. Columns with the same letter are not different at  $P < 0.05$  within a soil. CON = control; HS1 = hydrosolid #1; CKD = cement kiln dust; HS2 = hydrosolid #2; RM = bauxite red mud.

## CHAPTER II.

### USE OF ALUM SLUDGE (HYDROSOLIDS) TO REDUCE NON-POINT SOURCE PHOSPHORUS FROM AGRICULTURAL LAND IN RUNOFF WATER

#### ABSTRACT

Phosphorus losses in runoff water from land receiving surface application of poultry litter is becoming a non-point source (NPS) problem to sensitive watersheds and may result in eutrophication of surface waters. The beneficial use of two drinking water treatment alum sludges (hydrosolids) to reduce P in runoff water from land treated with poultry litter was evaluated. Poultry litter ( $6.5 \text{ Mg ha}^{-1}$ ) was applied to box plots containing fescue (*Festuca arundinacea*) to simulate permanent pasture typical of the Southeastern U.S. Hydrosolid treatments were a completely randomized design with three replications. Treatments included two types of hydrosolids (HS1, HS2) with broadcast and buffer strip application methods. Simulated rainfall from a single oscillating nozzle was applied to fescue boxes at a rate of  $3.8 \text{ cm h}^{-1}$  for 84 minutes. Concentration and total mass of soluble phosphorus (P), total P, and total aluminum (Al) in runoff samples were determined. Hydrosolid application significantly reduced the concentration

and total mass of soluble P and total P in runoff water ( $P < 0.05$ ). Only slight or no increases in total Al concentration and mass in runoff water was found. The buffer strip application appears to be more effective than the broadcast application in reducing the concentration (Table 2) and mass (Table 3) of cumulative soluble and total P in runoff water. Perhaps better contact between P in the runoff water and the hydrosolid particles occurred in the buffer strip than the broadcast application. Both hydrosolids reduced P similarly for the contact times of the runoff study. Crushing of hydrosolids to finer (<0.2 mm) particles will increase surface area and P adsorption capacity, thus increasing the ability of the hydrosolids to reduce P in runoff water. Land application of hydrosolids may provide a safe and inexpensive solution to control phosphorus runoff from agricultural land. Hydrosolid application to agricultural land treated with animal manure in sensitive watersheds may improve drinking water quality and provide financial savings for municipalities.

## INTRODUCTION

The land application of poultry litter and swine manure to agricultural lands provides an economical means of supplying beneficial nutrients to crops. However, field applications of poultry litter and swine manure at rates to meet forage nitrogen requirements normally exceeds phosphorus (P) crop requirements and results in excessive levels of soil P (Shreve et al., 1995). Phosphorus losses in runoff water from land receiving surface application of poultry litter is becoming a non-point source (NPS) problem to sensitive watersheds (Edwards and Daniel, 1993; Sharpley and Menzel, 1987) and may result in eutrophication of surface waters.

Recent benchmark Conservation Practice Standard and Waste Utilization guidelines passed by the Oklahoma Natural Resource Conservation Service (NRCS) limit animal manure applications to soils with excessive amounts of bioavailable P (NRCS, 1994). These guidelines were designed to determine the application rate of animal manure beneficial to soils in sensitive watersheds. Application rate is based on preventing excessive accumulation of P in soil. The Concentrated Animal Feeding Operations (CAFO) regulations in U.S. EPA Region VI have adopted the use of NRCS guidelines that limit application of animal manures to P sensitive watersheds. Runoff P will increase



with an increase in bioavailable P in soils (Sharpley, 1992). Reduction of bioavailable P in soils that exceed CAFO levels would reduce the NPS threat to sensitive watersheds.

Land application of alum (aluminum sulfate) has long since been used to reduce lake sediment P release (Kennedy and Cooke, 1982; Knauer and Garrison, 1981; Welch et al., 1982; and Young et al., 1988). Litter amended with alum to reduce P solubility in runoff water on agricultural lands with excessive P has also been investigated (Shreve et al., 1995). They found that soluble and total P were significantly reduced. Coale et al. (1994) mixed municipal drinking water purification facility waste material (alum sludge) with soil in a column and reduced P concentration in drainage water.

Surface application of nonhazardous alum sludges (hydrosolids) that reduce P solubility through precipitation and/or adsorption reactions to agricultural lands treated with poultry litter would effectively reduce the potential for P loss in runoff. The beneficial use of two drinking water treatment hydrosolids (HS1, HS2) to reduce P in runoff water were evaluated in this study.

## MATERIALS AND METHODS

Small-scale plots (fescue boxes) in a controlled greenhouse environment were used in the runoff study. Eighteen boxes which measured 1.0 meter square by 0.33 meter deep were used with a perforated bottom to hold soil and grow fescue in an effort to simulate permanent pasture typical of much of the Southeastern U.S. Boxes were constructed to determine the effects of rainfall, slope, and vegetation height on runoff water quality from fescue plots treated with poultry litter (Olson, 1995). The description of the boxes used in this study as constructed by Olson is as follows.

The fescue (*Festuca arundinacea*) boxes were constructed from a supporting frame of heavy angle iron with treated plywood attached as the sides of the box. Four steel rods provided the support for the bottom of the box. The steel rods also supported a section of expanded metal (4.76 mm) on which a piece of fine mesh polyethylene screening was then attached. The boxes were filled to a depth of 5 cm with a gravel/sand mixture (Fig. 1). The gravel/sand layer was covered with 2.5 cm of coarse sand. The remaining volume was filled with a Baxter silt loam (clayey, mixed, mesic, Typic Paleudult) from Delaware County, Oklahoma. The plywood side on the front of the box was cut 2.5 cm lower than the other three sides so runoff could leave the plot. A flume made of galvanized metal was attached to the lower side to direct runoff. To make the

fescue boxes retrievable, four 10 cm X 10 cm wooden blocks were bolted on the bottom of each box at the corners to allow access by a floor dolly and forklift.

The fescue used in this study was maintained by watering with a soaker hose. One day prior to the rainfall event, the fescue was trimmed to 7.6 cm to simulate typical field conditions for poultry litter application. Poultry litter was applied by hand to the box surface with special attention devoted to the uniformity of application. One application rate of 6.5 Mg ha<sup>-1</sup> was used in this experiment.

The experimental design was a completely randomized design with three replications. Two types of hydrosolids (HS1 and HS2) were investigated. Both hydrosolids were alum sludges from municipal drinking water treatment plants and are described in Chapter 1 of this thesis. Due to lack of uniformity in hydrosolid size, both hydrosolids were crushed to <6 mm size. Hydrosolids were applied to box plots by broadcasting or as a buffer strip (Fig. 2). The buffer strip was approximately 7.6 cm from the runoff flume and 10.2 cm wide. Broadcast amendments were applied generously across the box starting 7.6 cm from the runoff flume being careful to give equal application over the fescue.

Surface residue and fescue cover measurements were conducted to show uniformity of boxes. Percent of blade, debris, and ground cover on the box surface were evaluated by using a simple point measurement system where a pointed rod was placed downward toward the soil surface. The rod was guided by a ridge frame that had 10 sets of holes. The frame was set on the box surface and rods were slowly pushed through the guides toward the soil surface. The first material that the tip of the rod touched was the

measured recording for that sampling point. The three possible types of material to characterize the cover of the plots are defined as follows:

BLADE - any living green material such as a leaf or stem

DEBRIS - any nonliving material such as leaf litter

GROUND - bare uncovered soil

Once the first ten measurements were taken, the frame was rotated on the vertical axis 90° and another ten measurements were taken in the same manner. The 20 sampling points were used to determine the percentage of blade, debris, and ground.

The quantity of forage on each box before the treatments were applied was also determined by clipping all the forage from a small area of each box. The area clipped was defined by a square frame with inside dimensions measuring 10 cm X 10 cm. The square was tossed on the box surface and all of the forage that was rooted inside the frame was harvested, bagged, and oven dried at 95°C for 24 h.

Four boxes were used in a preliminary study to determine the hydrosolid amendment rate. Hydrosolid #2 (HS2) was used for the preliminary study at 5.0 Mg ha<sup>-1</sup> and 10 Mg ha<sup>-1</sup> rates with 6.5 Mg ha<sup>-1</sup> poultry litter. Poultry litter samples were collected and analyzed for total Kjeldahl nitrogen (TKN), total P (TP), and percent moisture. TKN, on a dry basis, was 55.0 g kg<sup>-1</sup>, TP dry was 15.7 g kg<sup>-1</sup>, and percent moisture was 215 g kg<sup>-1</sup>. The hydrosolid was tested as a buffer strip and as a broadcast application. Runoff was collected and analyzed for soluble P reduction.

Hydrosolid #1 (HS1) was applied at a 15 Mg ha<sup>-1</sup> rate and HS2 was applied at a 10 Mg ha<sup>-1</sup> rate. It was noted after the selection of amendment rates that HS2 caused

significant damming of runoff water. A 10 Mg ha<sup>-1</sup> rate was later selected to allow the runoff to pass through the buffer strip. Amendment rates were determined from the preliminary study.

The rainfall simulator was constructed and described by Olson (1995). The rainfall simulator used is a modified design of the Kentucky Rainfall Simulator described by Moore et al. (1983). The rainfall simulator was designed to allow fescue boxes to tilt and accommodate different slope settings. The simulator used in this study consists of a single oscillating nozzle which travels back and forth across the fescue boxes and between two return pans. The simulator utilizes a Veejet 80100 nozzle with an operating pressure at the nozzle of 41 kPa to achieve the drop size and kinetic energy typical of natural rainfall (Meyer and Harmon, 1979).

Runoff collection was similar to that described by Olson (1995). Runoff was collected in a tank that rested on a balance with two strain gauges, one on either side. The strain gauges are electronic sensors that measure weight (in kg) of runoff in the collection tank. A data-logger recorded the strain gauge readings every 15 seconds for the duration of the storm event. This information was then downloaded to a personal computer and later summarized as a mass flow rate runoff hydrograph.

The rain simulator was electronically programmed to deliver 3.8 cm h<sup>-1</sup> over an 84 minute rainfall duration (Olson, 1995). The experiment was conducted in a greenhouse where temperatures ranged from 27 to 35°C. Boxes were saturated with water and allowed to drain for 72 hours prior to simulated rainfall. Poultry litter and amendments were applied to the fescue boxes and placed in the rainfall simulator by a forklift. Boxes

were tilted at a 5% slope. A plastic tarp was attached to the front of the fescue box and extended over the runoff weighing system to shield it from stray rainfall. Simulated rainfall rate was calibrated daily.

Runoff from fescue boxes was collected in a galvanized metal container. After 84 minutes of rainfall, the runoff was stirred vigorously for 2 to 3 minutes followed by collection of a 0.5 liter composite sample. Runoff samples were stored at -10°C. All chemical analysis were conducted within one week after sampling.

Soluble phosphorus (P), total P, and total aluminum (Al) in runoff samples were determined. Soluble P was measured on filtered (0.45  $\mu\text{m}$ ) runoff samples (Greenburg et al., 1992). Soluble P was measured by Murphy-Riley colorimetric method based on formation of phospho-molybdenum blue complex (Murphy and Riley, 1962).

Total P and total Al in unfiltered runoff samples were determined by wet digestion with  $\text{HNO}_3$ . Runoff samples (25 mL) were digested with 5 mL of  $\text{HNO}_3$  for 1.5 h and 150°C and diluted to volume (25 mL) with distilled water. Total P was measured by the Murphy-Riley Method (1962) and total Al by inductively coupled plasma atomic emission spectroscopy (ICP) instrumentation.

## RESULTS AND DISCUSSION

Uniformity of vegetation and debris distribution was determined by measuring surface coverage of blade, debris, ground, and forage density in randomly selected fescue boxes (Table 1). In general, the green living fescue (blade), the non-living fescue (debris), the uncovered soil (ground), and the forage density were similar ( $P < 0.05$ ) and indicated vegetation was uniform among boxes.

Treatment means of cumulative runoff flow volumes were determined from hydrographs (Fig. 3). Total runoff volumes appeared larger for broadcast vs. buffer applications for HS2, but not HS1. These trends suggest that the HS2 buffer strip application may have slowed water runoff from the box plots compared to the broadcast application. However, large amounts of variation were found in runoff volumes between box plots ( $LSD_{0.10} = 17.5$ ) making interpretation of the HS2 trend difficult.

The effects of hydrosolid application on concentration of soluble phosphorus (P), total P, and total aluminum (Al) in runoff water were determined (Table 2). Hydrosolid application significantly reduced the concentration of soluble P and total P ( $P < 0.05$ ). In general, buffer strip applications reduced the concentration of soluble P and total P more than broadcast application ( $P < 0.10$ ). Total Al, determined by wet digestion with  $HNO_3$ , was determined in runoff to ensure precipitated Al in the hydrosolid did not dissolve and

result in undesirable potential environmental impacts. In general, only slight or no increase in total Al concentration in runoff water was found (Table 3). The largest observed Al concentration of  $1.71 \text{ mg L}^{-1}$  was well below levels of  $>50 \text{ mg L}^{-1}$  associated with adverse effects of dissolved Al on plant growth (Sloan et al., 1995). Therefore, slight increases in total Al in runoff water should not result in adverse potential environmental impacts.

The effect of hydrosolid application on cumulative runoff losses of soluble P, total P, and total Al were determined (Table 3). Hydrosolid applications significantly reduced cumulative losses of soluble and total P compared to untreated plots ( $P < 0.05$ ). Similarly, Shreve et al. (1995) found that alum amended litter, with chemical properties similar to a hydrosolid, decreased soluble and total P load in runoff from fields treated with poultry litter. However, no information is available on alum sludge (hydrosolid) and P reduction in runoff. Buffer strip application of hydrosolids significantly decreased runoff loss of soluble P and total P compared to broadcast application for HS2 ( $P < 0.10$ ) and HS1 ( $P \cong 0.10$ ). Cumulative runoff of total Al was not increased ( $P < 0.10$ ) by hydrosolid application suggesting potentially adverse environmental impact from dissolved Al in runoff water is unlikely.

The buffer strip application appears to be more effective than the broadcast application in reduction of concentration (Table 2) and mass (Table 3) of cumulative soluble and total P in runoff water. Less runoff water was associated with the buffer strip compared to the broadcast application for HS2 (Fig. 3) suggesting buffer strip application may have resulted in greater infiltration of water in the plots. However, little difference in



runoff water volumes between buffer strip and broadcast applications were found for HS1 (Fig. 3). Most of the runoff water passed through the buffer strips on the box plots (Fig. 2). Perhaps better contact between P in the runoff water and the hydrosolid particles occurred in the buffer strip than the broadcast application.

In Chapter 1, results from soil incubated with hydrosolids for nine weeks showed HS2 reduced greater amounts of soluble P than HS1. Evidently the HS2 contained more calcium than HS1 and may have resulted in greater amounts of calcium phosphate precipitation. A batch equilibration study where  $150 \text{ mg L}^{-1}$  of soluble P was shaken with 1 g of hydrosolid was conducted to study the kinetics of the phosphate adsorption and/or precipitation. Although HS2 reduced more soluble P than HS1 at equilibration times exceeding 10 minutes, HS1 and HS2 reduced the same amount of soluble P for equilibration times less than 5 minutes (Fig. 4). Soluble P in runoff water was in contact for less than 2 minutes in the box plot study. These results suggest little difference in soluble P reduction was due to reaction kinetics. However, cumulative rainfall events may result in cumulative times that exceed 10 minutes. Therefore, with time, HS2 would more likely adsorb more P than HS1.

The particle size distribution affects surface area and should influence the adsorption properties of the hydrosolids. Adsorption of soluble P by both coarse (87% greater than 0.2 mm) and fine (100% less than 0.2 mm) forms of HS2 was studied to determine the importance of hydrosolid particle size (Fig. 5). The fine HS2 adsorbed more soluble P faster than coarse HS2. Crushing of hydrosolids to finer (<0.2 mm)

particles will increase surface area and P adsorption capacity, thus increasing the ability of the hydrosolids to reduce P in runoff water.

## SUMMARY

Non-point source phosphorus pollution from agricultural land treated with animal manures may be reduced by using municipal alum sludge (hydrosolids). Land application of hydrosolids may provide a safe and inexpensive solution to control phosphorus runoff from agricultural land. Hydrosolids should be surface applied when poultry litter is not incorporated into the soil. Hydrosolids can be broadcasted or applied as a buffer strip at the edge of the field. Buffer strips should be more effective than broadcasting in reduction of phosphorus in runoff water. Potential adverse environmental impacts from land application of hydrosolids are unlikely. However, potential environmental impacts from repeated application of hydrosolids are not addressed by this work.

Results from this study were completed on a small scale and may not be transferable to a large scale production. Other variables under field conditions (i.e. circulated flow) are scale dependent and may effect the ability of hydrosolids to reduce NPS. Further research is needed to evaluate the use of hydrosolids to reduce NPS phosphorus under field conditions.

Hydrosolid wastes are currently being landfilled at great expense to municipalities. Also, several municipal water treatment plants producing hydrosolids may have source water degraded by non-point source P pollution. Hydrosolid application to agricultural land treated with animal manure in sensitive watersheds may improve drinking water quality and provide financial savings for municipalities.

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Table 1. Mean Percent Cover and Forage Density of the Fescue Boxes.

Hydrosolid	Application	Blade	Debris	Ground	Forage
		----- % -----			kg ha <sup>-1</sup>
HS1	Buffer	35.0	30.0	35.0	3352
HS1	Broadcast	17.5	45.0	37.5	3430
HS2	Buffer	25.0	55.0	20.0	4185
HS2	Broadcast	27.5	42.5	30.0	2659
LSD ( $\alpha=0.05$ )		26.4	16.7	24.1	3804
LSD ( $\alpha=0.10$ )		20.7	13.1	18.9	2982

Table 2. The Effect of Hydrosolid Application on Mean Concentration of Soluble P, Total P, and Total Al in Runoff Water.

Hydrosolid	Application	Soluble P		Total P		Total Al				
		----- mg L <sup>-1</sup> -----								
HS1	Buffer Strip	bc	8.99	c	bc	8.77	c	ab	1.42	b
	Broadcast	b	13.0	b	b	12.9	b	bc	1.23	b
HS2	Buffer Strip	c	4.93	d	c	5.20	d	a	1.71	a
	Broadcast	bc	9.83	bc	b	9.87	bc	bc	1.22	bc
Control	6.5 Mg ha <sup>-1</sup> poultry manure	a	22.3	a	a	20.8	a	c	0.96	c
LSD ( $\alpha=0.05$ )			4.94			4.19			0.32	
LSD ( $\alpha=0.10$ )			4.02			3.41			0.26	

Letters to the left of application means represent LSD  $\alpha = 0.05$ .

Letters to the right of application means represent LSD  $\alpha = 0.10$ .

Table 3. The Effect of Hydrosolid Application on Mean Cumulative Runoff Losses for Soluble P, Total P, and Total Al

Hydrosolid	Application	Soluble P	Total P	Total Al
		----- mg box <sup>-1</sup> -----		
HS1	Buffer Strip	b 142 bc	b 141 bc	a 25.3 a
	Broadcast	b 278 b	ab 279 b	a 30.7 a
HS2	Buffer Strip	b 8.2 c	b 103 c	a 27.7 a
	Broadcast	b 285 b	ab 284 b	a 35.0 a
Control	6.5 Mg ha <sup>-1</sup> poultry litter	a 485 a	a 455 a	a 21.2 a
LSD ( $\alpha=0.05$ )		197	193	28.7
LSD ( $\alpha=0.10$ )		159	156	23.3

Letters to the left of application means represent LSD  $\alpha = 0.05$ .

Letters to the right of application means represent LSD  $\alpha = 0.10$ .



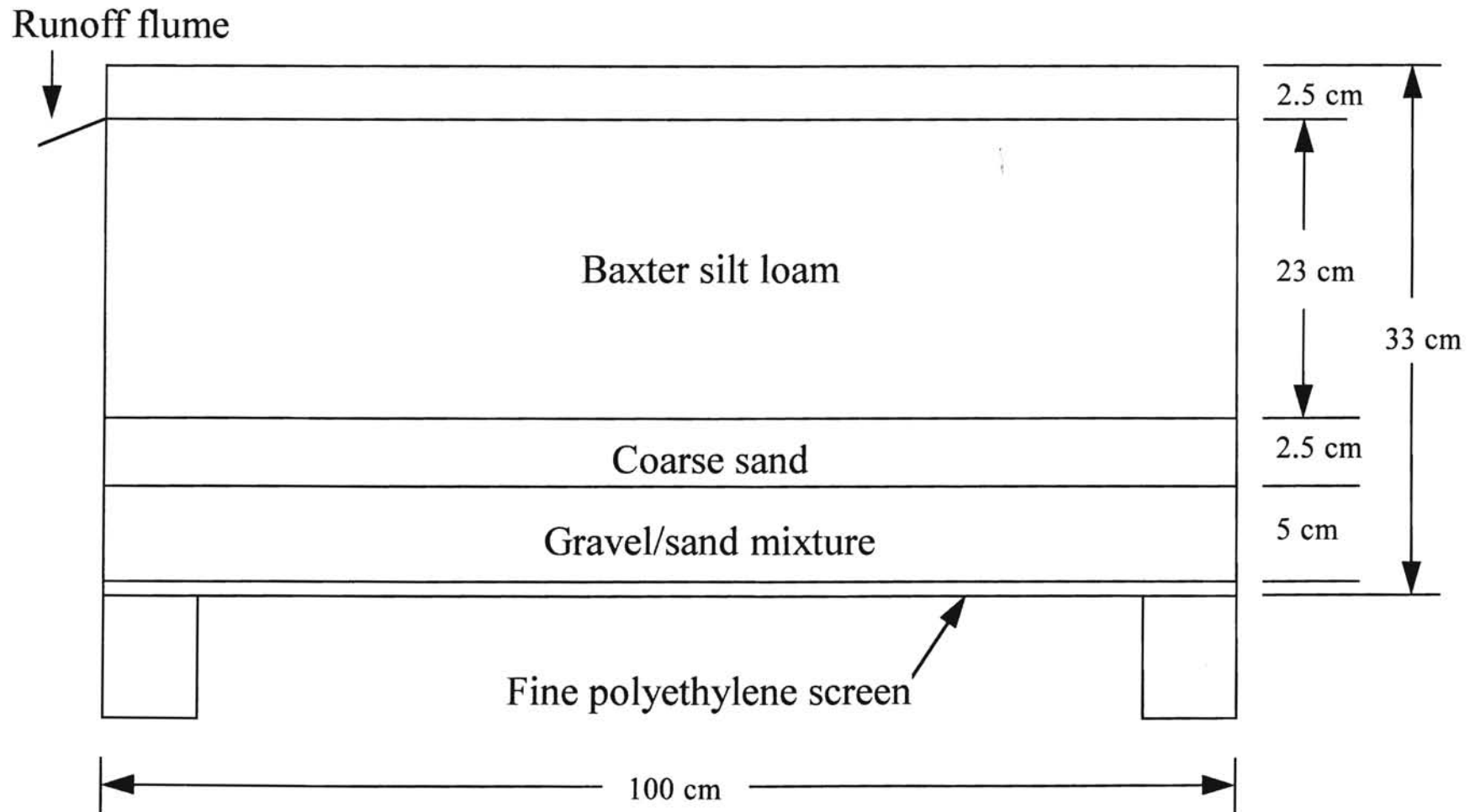


Figure 1. Box plot dimensions. (Not drawn to scale).

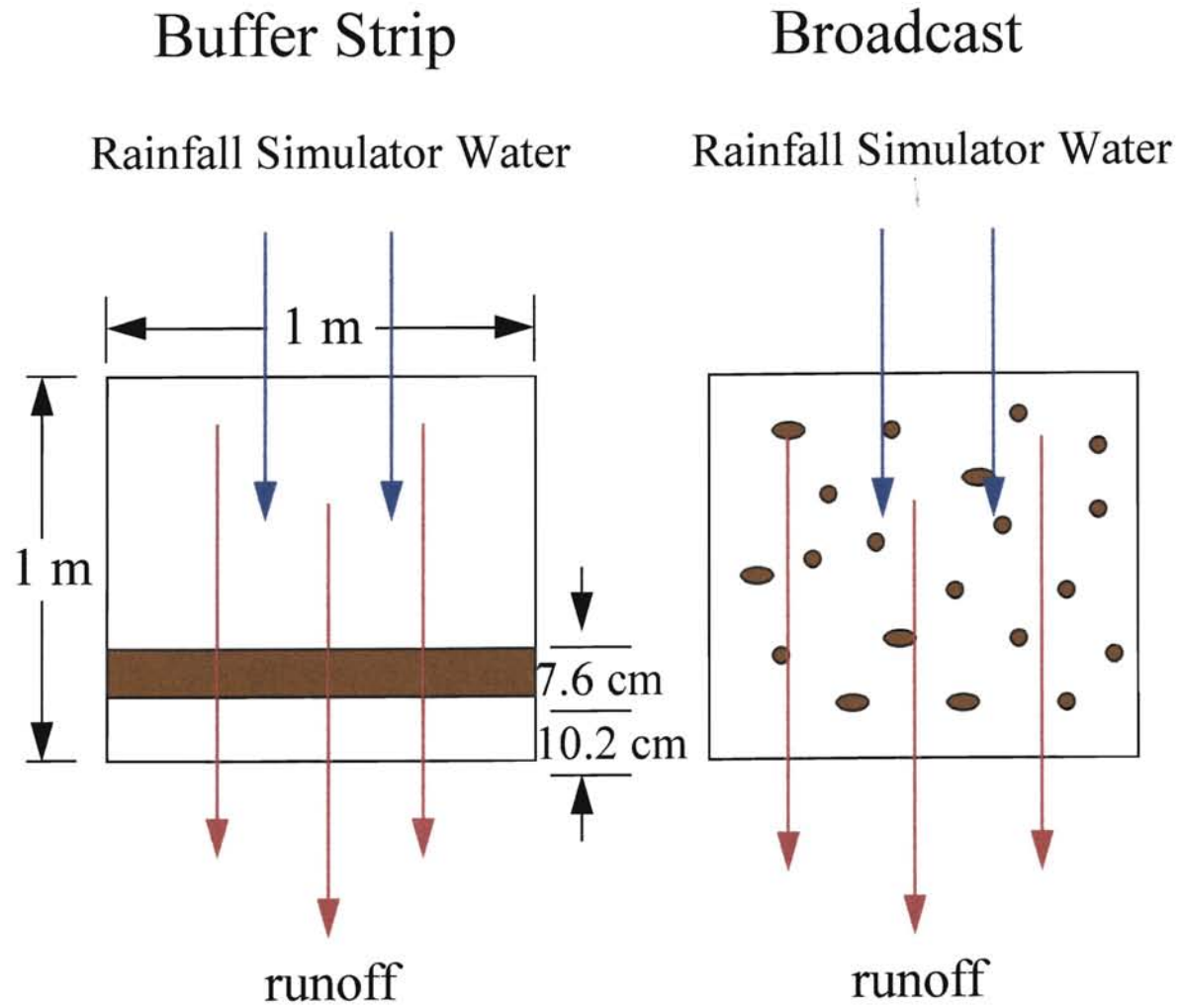


Figure 2. Buffer strip vs. Broadcast application.

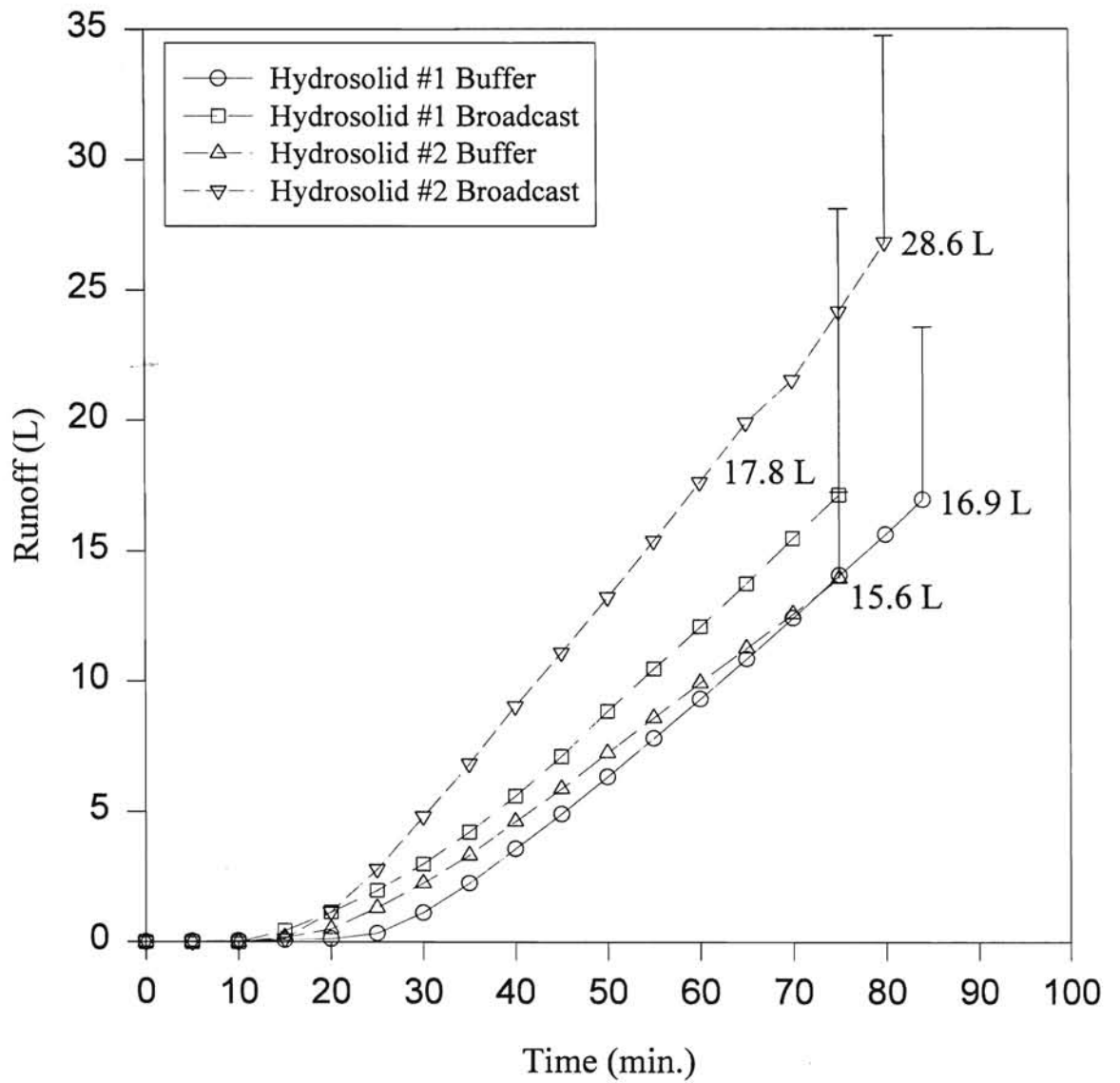


Figure 3. Mean cumulative runoff volume with time

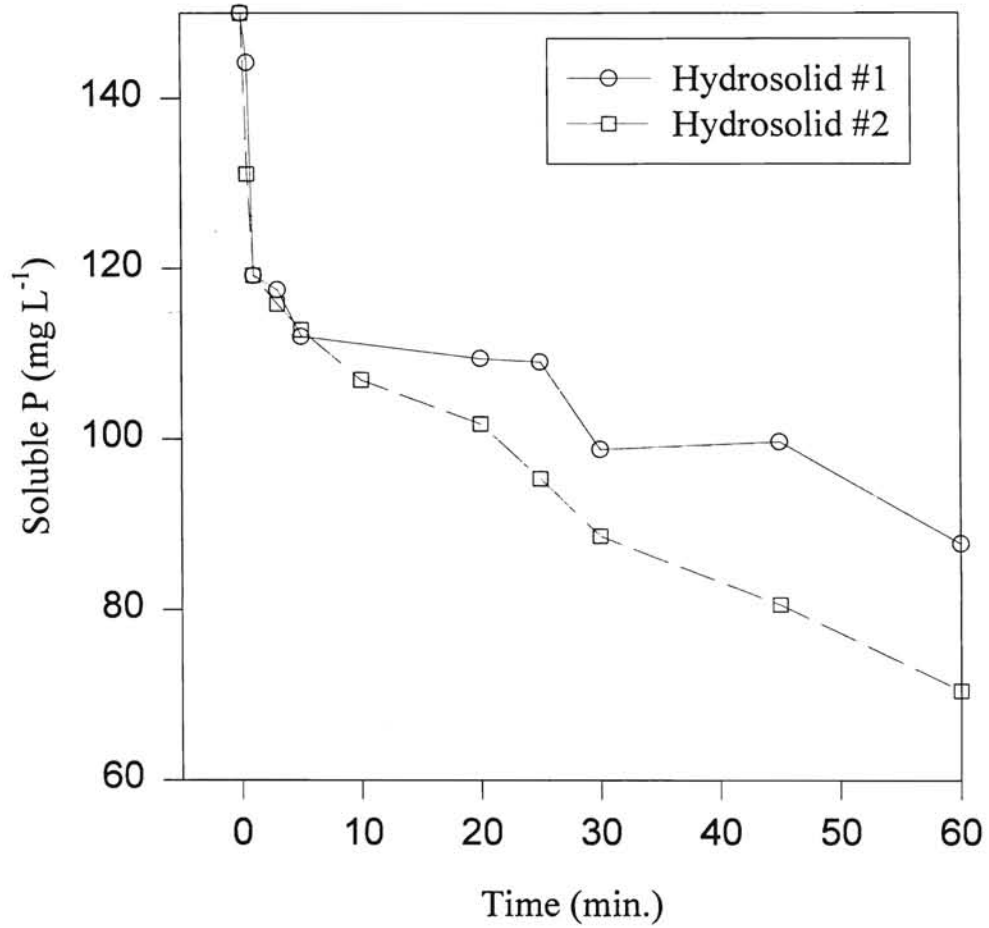


Figure 4. Batch equilibration of 150 mg L<sup>-1</sup> soluble P with Hydrosolid #1 and Hydrosolid #2 over time.

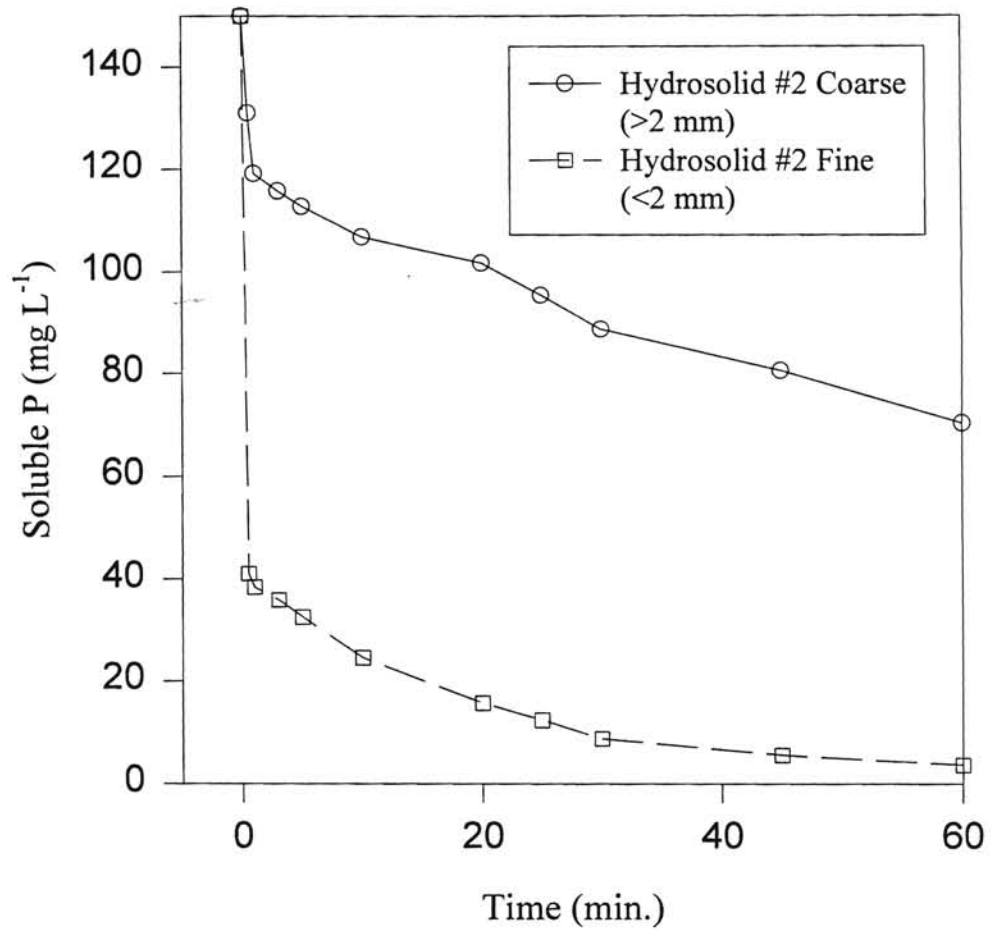


Figure 5. Amendment size effect on soluble P reduction of Hydrosolid #2 coarse and fine over time.

**APPENDIX**

Table A1. Incubation study Mehlich III reduction for 3 week sample time.

3 Weeks		Mehlich	amend	% amend.	abs.	ug in 0.25	dil extract	dil	extract	Mehlich	Mehlich	reduction	%	
Soil	soil ppm	soil ppm				ug/mL	factor	ug/mL	soil ppm	avg.	in ug/mL	removed		
Dickson #1	599	HS1	3	0.140	1.222	4.89	10	48.9	489		111	18.4%		
	599	HS1	3	0.129	1.126	4.50	10	45.0	450		149	24.9%		
	599	HS1	3	0.133	1.181	4.64	10	46.4	464	468	135	22.5%		
	599	CKD	3	0.106	0.925	3.70	10	37.0	370		229	38.3%		
	599	CKD	3	0.111	0.969	3.87	10	38.7	387		212	35.3%		
	599	CKD	3	0.105	0.916	3.66	10	36.6	366	375	233	38.8%		
	599	HS2	3	0.119	1.038	4.15	10	41.5	415		184	30.7%		
	599	HS2	3	0.104	0.908	3.63	10	36.3	363		236	39.4%		
	599	HS2	3	0.118	1.030	4.12	10	41.2	412	397	187	31.3%		
	599	Red Mud	3	0.120	1.047	4.19	10	41.9	419		180	30.1%		
	599	Red Mud	3	0.134	1.169	4.68	10	46.8	468		131	21.9%		
	599	Red Mud	3	0.126	1.099	4.40	10	44.0	440	442	159	26.6%		
	599	HS1	10	0.088	0.768	3.07	10	30.7	307		292	48.7%		
	599	HS1	10	0.097	0.846	3.39	10	33.9	339		261	43.5%		
	599	HS1	10	0.095	0.829	3.32	10	33.2	332	326	268	44.7%		
	599	CKD	10	0.084	0.733	2.93	10	29.3	293		306	51.1%		
	599	CKD	10	0.098	0.855	3.42	10	34.2	342		257	42.9%		
	599	CKD	10	0.091	0.794	3.18	10	31.8	318	318	282	47.0%		
	599	HS2	10	0.053	0.462	1.85	10	18.5	185		414	69.1%		
	599	HS2	10	0.076	0.663	2.65	10	26.5	265		334	55.7%		
	599	HS2	10	0.069	0.602	2.41	10	24.1	241	230	358	59.8%		
	599	Red Mud	10	0.092	0.803	3.21	10	32.1	321		278	48.4%		
	599	Red Mud	10	0.100	0.873	3.49	10	34.9	349		250	41.7%		
	599	Red Mud	10	0.114	0.995	3.98	10	39.8	398	356	201	33.6%		
			Con.	N/A	0.169	1.475	5.90	10	59.0	590				
			Con.	N/A	0.171	1.492	5.97	10	59.7	597				
			Con.	N/A	0.175	1.527	6.11	10	61.1	611	599			
	Dickson #2	467	HS1	3	0.113	0.986	3.94	10	39.4	394		072	15.5%	
		467	HS1	3	0.115	1.003	4.01	10	40.1	401		065	14.0%	
		467	HS1	3	0.111	0.969	3.87	10	38.7	387	394	079	17.0%	
		467	CKD	3	0.088	0.768	3.07	10	30.7	307		159	34.2%	
		467	CKD	3	0.094	0.820	3.28	10	32.8	328		139	29.7%	
		467	CKD	3	0.099	0.864	3.46	10	34.6	346	327	121	25.9%	
467		HS2	3	0.108	0.942	3.77	10	37.7	377		090	19.2%		
467		HS2	3	0.104	0.908	3.63	10	36.3	363		104	22.2%		
467		HS2	3	0.111	0.969	3.87	10	38.7	387	376	079	17.0%		
467		Red Mud	3	0.108	0.942	3.77	10	37.7	377		090	19.2%		
467		Red Mud	3	0.122	1.065	4.26	10	42.6	426		041	08.7%		
467		Red Mud	3	0.107	0.934	3.73	10	37.3	373	392	093	20.0%		
467		HS1	10	0.092	0.803	3.21	10	32.1	321		145	31.2%		
467		HS1	10	0.106	0.925	3.70	10	37.0	370		097	20.7%		
467		HS1	10	0.102	0.890	3.56	10	35.6	356	349	111	23.7%		
467		CKD	10	0.087	0.759	3.04	10	30.4	304		163	34.9%		
467		CKD	10	0.079	0.689	2.76	10	27.6	276		191	40.9%		
467		CKD	10	0.081	0.707	2.83	10	28.3	283	287	184	39.4%		
467		HS2	10	0.061	0.532	2.13	10	21.3	213		254	54.4%		
467		HS2	10	0.066	0.576	2.30	10	23.0	230		236	50.6%		
467		HS2	10	0.062	0.541	2.16	10	21.6	216	220	250	53.6%		
467		Red Mud	10	0.079	0.689	2.76	10	27.6	276		191	40.9%		
467		Red Mud	10	0.082	0.716	2.86	10	28.6	286		180	38.7%		
467		Red Mud	10	0.086	0.750	3.00	10	30.0	300	287	166	35.7%		
			Con.	N/A	0.120	1.047	4.19	10	41.9	419				
			Con.	N/A	0.137	1.195	4.78	10	47.8	478				
			Con.	N/A	0.144	1.257	5.03	10	50.3	503	467			
Keokuk		311	HS1	3	0.069	0.602	2.41	10	24.1	241		070	22.5%	
		311	HS1	3	0.070	0.611	2.44	10	24.4	244		066	21.3%	
		311	HS1	3	0.071	0.620	2.48	10	24.8	248	244	063	20.2%	
		311	CKD	3	0.078	0.681	2.72	10	27.2	272		038	12.3%	
		311	CKD	3	0.087	0.759	3.04	10	30.4	304		007	02.2%	
		311	CKD	3	0.084	0.733	2.93	10	29.3	293	290	017	05.6%	
	311	HS2	3	0.076	0.663	2.65	10	26.5	265		045	14.6%		
	311	HS2	3	0.074	0.646	2.58	10	25.8	258		052	16.8%		
	311	HS2	3	0.080	0.698	2.79	10	27.9	279	268	031	10.1%		
	311	Red Mud	3	0.094	0.820	3.28	10	32.8	328		-017	-05.6%		
	311	Red Mud	3	0.082	0.716	2.86	10	28.6	286		024	07.9%		
	311	Red Mud	3	0.086	0.750	3.00	10	30.0	300	305	010	03.4%		
	311	HS1	10	0.058	0.506	2.02	10	20.2	202		108	34.8%		
	311	HS1	10	0.062	0.541	2.16	10	21.6	216		094	30.3%		
	311	HS1	10	0.068	0.593	2.37	10	23.7	237	219	073	23.6%		
	311	CKD	10	0.066	0.576	2.30	10	23.0	230		080	25.8%		
	311	CKD	10	0.063	0.550	2.20	10	22.0	220		091	29.2%		
	311	CKD	10	0.064	0.558	2.23	10	22.3	223	225	087	28.1%		
	311	HS2	10	0.044	0.384	1.54	10	15.4	154		157	50.6%		
	311	HS2	10	0.038	0.332	1.33	10	13.3	133		178	57.3%		
	311	HS2	10	0.037	0.323	1.29	10	12.9	129	138	181	58.4%		
	311	Red Mud	10	0.069	0.602	2.41	10	24.1	241		070	22.5%		
	311	Red Mud	10	0.062	0.541	2.16	10	21.6	216		094	30.3%		
	311	Red Mud	10	0.069	0.602	2.41	10	24.1	241	267	070	22.5%		
			Con.	N/A	0.093	0.812	3.25	10	32.5	325				
		Con.	N/A	0.089	0.777	3.11	10	31.1	311					
		Con.	N/A	0.085	0.742	2.97	10	29.7	297	311				

Table A2. Incubation study pH changes for 3 week sample time

3 Weeks							
Soil	initial pH	amend	% amend.	pH	avg.	pH incr.	
Dickson #1	5.3	HS1	3	5.6		0.3	
	5.3	HS1	3	5.5		0.2	
	5.3	HS1	3	5.5	5.5	0.2	
	5.3	CKD	3	7.3		2	
	5.3	CKD	3	7.3		2	
	5.3	CKD	3	7.4	7.3	2.1	
	5.3	HS2	3	6.3		1	
	5.3	HS2	3	6.3		1	
	5.3	HS2	3	6.2	6.3	0.9	
	5.3	Red Mud	3	6.7		1.4	
	5.3	Red Mud	3	6.7		1.4	
	5.3	Red Mud	3	6.7	6.7	1.4	
	5.3	HS1	10	5.9		0.6	
	5.3	HS1	10	5.7		0.4	
	5.3	HS1	10	5.7	5.8	0.4	
	5.3	CKD	10	8.3		3	
	5.3	CKD	10	8.3		3	
	5.3	CKD	10	8.4	8.3	3.1	
	5.3	HS2	10	7.2		1.9	
	5.3	HS2	10	7		1.7	
	5.3	HS2	10	7.1	7.1	1.8	
	5.3	Red Mud	10	7.4		2.1	
	5.3	Red Mud	10	7.4		2.1	
	5.3	Red Mud	10	7.4	7.4	2.1	
			Con.	N/A	5.3		
			Con.	N/A	5.2		
			Con.	N/A	5.3	5.3	
	Dickson #2	5.8	HS1	3	5.9		0.1
		5.8	HS1	3	5.9		0.1
		5.8	HS1	3	5.9	5.9	0.1
		5.8	CKD	3	7.3		1.5
		5.8	CKD	3	7.3		1.5
		5.8	CKD	3	7.4	7.3	1.6
		5.8	HS2	3	6.6		0.8
		5.8	HS2	3	6.5		0.7
5.8		HS2	3	6.6	6.6	0.8	
5.8		Red Mud	3	6.9		1.1	
5.8		Red Mud	3	6.9		1.1	
5.8		Red Mud	3	7	6.9	1.2	
5.8		HS1	10	6.3		0.5	
5.8		HS1	10	6.3		0.5	
5.8		HS1	10	6.3	6.3	0.5	
5.8		CKD	10	8.2		2.4	
5.8		CKD	10	8.3		2.5	
5.8		CKD	10	8.2	8.2	2.4	
5.8		HS2	10	7.3		1.5	
5.8		HS2	10	7.2		1.4	
5.8		HS2	10	7.2	7.2	1.4	
5.8		Red Mud	10	7.3		1.5	
5.8		Red Mud	10	7.4		1.6	
5.8		Red Mud	10	7.4	7.4	1.6	
			Con.	N/A	5.9		
			Con.	N/A	5.8		
			Con.	N/A	5.8	5.8	
Keokuk		8.2	HS1	3	7.8		-0.4
		8.2	HS1	3	7.8		-0.4
		8.2	HS1	3	7.8	7.8	-0.4
		8.2	CKD	3	8.5		0.3
		8.2	CKD	3	8.5		0.3
		8.2	CKD	3	8.5	8.5	0.3
		8.2	HS2	3	7.9		-0.3
		8.2	HS2	3	7.9		-0.3
	8.2	HS2	3	7.9	7.9	-0.3	
	8.2	Red Mud	3	8		-0.2	
	8.2	Red Mud	3	8		-0.2	
	8.2	Red Mud	3	8	8.0	-0.2	
	8.2	HS1	10	7.8		-0.4	
	8.2	HS1	10	7.9		-0.3	
	8.2	HS1	10	7.8	7.8	-0.4	
	8.2	CKD	10	8.5		0.3	
	8.2	CKD	10	8.5		0.3	
	8.2	CKD	10	8.6	8.5	0.4	
	8.2	HS1	10	8		-0.2	
	8.2	HS1	10	8		-0.2	
	8.2	HS1	10	8	8.0	-0.2	
	8.2	Red Mud	10	8.2		0	
	8.2	Red Mud	10	8.1		-0.1	
	8.2	Red Mud	10	8.2	8.2	0	
			Con.	N/A	8.2		
			Con.	N/A	8.1		
			Con.	N/A	8.2	8.2	



Table A3. Incubation study Mehlich III reduction for 5 week sample time.

5 Weeks													
Soil	Mehlich soil ppm	amend	% amend.	abs.	ug in 0.25	dil extract ug/mL	dil factor	extract ug/mL	Mehlich soil ppm	Mehlich avg.	reduction in ug/mL	% removed	
Dickson #1	556	HS1	3	0.137	1.20	4.78	10	47.8	478		77.9	14.0%	
	556	HS1	3	0.155	1.35	5.41	10	54.1	541		15.1	2.7%	
	556	HS1	3	0.141	1.23	4.92	10	49.2	492	504	64.0	11.5%	
	556	CKD	3	0.101	0.88	3.53	10	35.3	353		203.6	36.6%	
	556	CKD	3	0.121	1.06	4.22	10	42.2	422		133.8	24.1%	
	556	CKD	3	0.109	0.95	3.80	10	38.0	380	385	175.6	31.6%	
	556	HS2	3	0.115	1.00	4.01	10	40.1	401		154.7	27.8%	
	556	HS2	3	0.124	1.08	4.33	10	43.3	433		123.3	22.2%	
	556	HS2	3	0.121	1.06	4.22	10	42.2	422	419	133.8	24.1%	
	556	Red Mud	3	0.128	1.12	4.47	10	44.7	447		109.3	19.7%	
	556	Red Mud	3	0.146	1.27	5.10	10	51.0	510		46.5	8.4%	
	556	Red Mud	3	0.125	1.09	4.36	10	43.6	436	464	119.8	21.5%	
	556	HS1	10	0.093	0.81	3.25	10	32.5	325		231.5	41.6%	
	556	HS1	10	0.092	0.80	3.21	10	32.1	321		235.0	42.3%	
	556	HS1	10	0.118	1.03	4.12	10	41.2	412	353	144.2	25.9%	
	556	CKD	10	0.097	0.85	3.39	10	33.9	339		217.5	39.1%	
	556	CKD	10	0.079	0.69	2.76	10	27.6	276		280.4	50.4%	
	556	CKD	10	0.075	0.65	2.62	10	26.2	262	292	294.3	52.9%	
	556	HS2	10	0.039	0.34	1.36	10	13.6	136		420.0	75.5%	
	556	HS2	10	0.071	0.62	2.48	10	24.8	248		308.3	55.4%	
	556	HS2	10	0.074	0.65	2.58	10	25.8	258	214	297.8	53.6%	
	556	Red Mud	10	0.108	0.94	3.77	10	37.7	377		179.1	32.2%	
	556	Red Mud	10	0.103	0.90	3.60	10	36.0	360		196.6	35.4%	
	556	Red Mud	10	0.103	0.90	3.60	10	36.0	360	365	196.6	35.4%	
	556	Con.	N/A		0.153	1.34	5.34	10	53.4	534			
	556	Con.	N/A		0.161	1.40	5.62	10	56.2	562			
	556	Con.	N/A		0.164	1.43	5.72	10	57.2	572	556		
	Dickson #2	476	HS1	3	0.124	1.08	4.33	10	43.3	433		43.1	9.1%
		476	HS1	3	0.122	1.06	4.26	10	42.6	426		50.1	10.5%
		476	HS1	3	0.126	1.10	4.40	10	44.0	440	433	36.1	7.6%
		476	CKD	3	0.095	0.83	3.32	10	33.2	332		144.3	30.3%
		476	CKD	3	0.087	0.76	3.04	10	30.4	304		172.2	36.2%
		476	CKD	3	0.095	0.83	3.32	10	33.2	332	322	144.3	30.3%
		476	HS2	3	0.111	0.97	3.87	10	38.7	387		88.5	18.6%
		476	HS2	3	0.110	0.96	3.84	10	38.4	384		92.0	19.3%
476		HS2	3	0.109	0.95	3.80	10	38.0	380	384	95.4	20.1%	
476		Red Mud	3	0.117	1.02	4.08	10	40.8	408		67.5	14.2%	
476		Red Mud	3	0.119	1.04	4.15	10	41.5	415		60.5	12.7%	
476		Red Mud	3	0.095	0.83	3.32	10	33.2	332	385	144.3	30.3%	
476		HS1	10	0.089	0.78	3.11	10	31.1	311		165.3	34.7%	
476		HS1	10	0.101	0.88	3.53	10	35.3	353		123.4	25.9%	
476		HS1	10	0.105	0.92	3.66	10	36.6	366	343	109.4	23.0%	
476		CKD	10	0.076	0.66	2.65	10	26.5	265		210.6	44.3%	
476		CKD	10	0.078	0.68	2.72	10	27.2	272		203.6	42.8%	
476		CKD	10	0.090	0.79	3.14	10	31.4	314	284	161.8	34.0%	
476		HS2	10	0.063	0.55	2.20	10	22.0	220		256.0	53.8%	
476		HS2	10	0.059	0.51	2.06	10	20.6	206		270.0	56.7%	
476		HS2	10	0.065	0.57	2.27	10	22.7	227	218	249.0	52.3%	
476		Red Mud	10	0.081	0.71	2.83	10	28.3	283		193.2	40.6%	
476		Red Mud	10	0.082	0.72	2.86	10	28.6	286		189.7	39.9%	
476		Red Mud	10	0.080	0.70	2.79	10	27.9	279	283	196.7	41.3%	
476		Con.	N/A		0.142	1.24	4.96	10	49.6	496			
476	Con.	N/A		0.124	1.08	4.33	10	43.3	433				
476	Con.	N/A		0.143	1.25	4.99	10	49.9	499	476			
Keokuk	304	HS1	3	0.072	0.63	2.51	10	25.1	251		52.4	17.3%	
	304	HS1	3	0.069	0.60	2.41	10	24.1	241		62.9	20.7%	
	304	HS1	3	0.061	0.53	2.13	10	21.3	213	235	90.8	29.9%	
	304	CKD	3	0.078	0.68	2.72	10	27.2	272		31.4	10.4%	
	304	CKD	3	0.084	0.73	2.93	10	29.3	293		10.5	3.5%	
	304	CKD	3	0.070	0.61	2.44	10	24.4	244	270	59.4	19.5%	
	304	HS2	3	0.065	0.57	2.27	10	22.7	227		76.8	25.3%	
	304	HS2	3	0.061	0.53	2.13	10	21.3	213		90.8	29.9%	
	304	HS2	3	0.063	0.55	2.20	10	22.0	220	220	83.8	27.6%	
	304	Red Mud	3	0.047	0.41	1.64	10	16.4	164		139.7	46.0%	
	304	Red Mud	3	0.073	0.64	2.55	10	25.5	255		48.9	16.1%	
	304	Red Mud	3	0.069	0.60	2.41	10	24.1	241	220	62.9	20.7%	
	304	HS1	10	0.059	0.51	2.06	10	20.6	206		97.8	32.2%	
	304	HS1	10	0.052	0.45	1.82	10	18.2	182		122.2	40.2%	
	304	HS1	10	0.052	0.45	1.82	10	18.2	182	190	122.2	40.2%	
	304	CKD	10	0.060	0.52	2.09	10	20.9	209		94.3	31.0%	
	304	CKD	10	0.063	0.55	2.20	10	22.0	220		83.8	27.6%	
	304	CKD	10	0.063	0.55	2.20	10	22.0	220	216	83.8	27.6%	
	304	HS2	10	0.036	0.31	1.26	10	12.6	126		178.0	58.6%	
	304	HS2	10	0.033	0.29	1.15	10	11.5	115		188.5	62.1%	
304	HS2	10	0.036	0.31	1.26	10	12.6	126	122	178.0	58.6%		
304	Red Mud	10	0.061	0.53	2.13	10	21.3	213		90.8	29.9%		
304	Red Mud	10	0.062	0.54	2.16	10	21.6	216		87.3	28.7%		
304	Red Mud	10	0.056	0.49	1.95	10	19.5	195	243	108.2	35.6%		
304	con.	N/A		0.085	0.74	2.97	10	29.7	297				
304	con.	N/A		0.084	0.73	2.93	10	29.3	293				
304	con.	N/A		0.092	0.80	3.21	10	32.1	321	304			

Table A4. Incubation Study Mehlich III reduction for 9 week sample time.

9 Weeks														
Soil	Mehlich soil ppm	amend.	% amend.	abs.	ug in 0.25	dil extract ug/mL	dil factor	extract ug/mL	Mehlich soil ppm	Mehlich avg.	reduction in ug/mL	% removed		
Dickson #1	554	HS1	3	0.134	1.17	4.68	10	46.8	468		86.1	15.5%		
	554	HS1	3	0.125	1.09	4.36	10	43.6	436		117.5	21.2%		
	554	HS1	3	0.119	1.04	4.15	10	41.5	415	440	138.4	25.0%		
	554	CKD	3	0.111	0.97	3.87	10	38.7	387		166.4	30.0%		
	554	CKD	3	0.110	0.96	3.84	10	38.4	384		169.9	30.7%		
	554	CKD	3	0.110	0.96	3.84	10	38.4	384	385	169.9	30.7%		
	554	HS2	3	0.096	0.84	3.35	10	33.5	335		218.7	39.5%		
	554	HS2	3	0.114	0.99	3.98	10	39.8	398		155.9	28.1%		
	554	HS2	3	0.122	1.06	4.26	10	42.6	426	386	128.0	23.1%		
	554	Red Mud	3	0.135	1.18	4.71	10	47.1	471		82.6	14.9%		
	554	Red Mud	3	0.143	1.25	4.99	10	49.9	499		54.7	9.9%		
	554	Red Mud	3	0.142	1.24	4.96	10	49.6	496	489	58.2	10.5%		
	554	HS1	10	0.100	0.87	3.49	10	34.9	349		204.8	37.0%		
	554	HS1	10	0.112	0.98	3.91	10	39.1	391		162.9	29.4%		
	554	HS1	10	0.102	0.89	3.56	10	35.6	356	365	197.8	35.7%		
	554	CKD	10	0.105	0.92	3.66	10	36.6	366		187.3	33.8%		
	554	CKD	10	0.103	0.90	3.60	10	36.0	360		194.3	35.1%		
	554	CKD	10	0.099	0.86	3.46	10	34.6	346	357	208.3	37.6%		
	554	HS2	10	0.060	0.52	2.09	10	20.9	209		344.4	62.2%		
	554	HS2	10	0.083	0.72	2.90	10	29.0	290		264.1	47.7%		
	554	HS2	10	0.069	0.60	2.41	10	24.1	241	247	313.0	56.5%		
	554	Red Mud	10	0.104	0.91	3.63	10	36.3	363		190.8	34.5%		
	554	Red Mud	10	0.096	0.84	3.35	10	33.5	335		218.7	39.5%		
	554	Red Mud	10	0.096	0.84	3.35	10	33.5	335	344	218.7	39.5%		
	554	Con.	N/A		0.151	1.32	5.27	10	52.7	527				
	554	Con.	N/A		0.154	1.34	5.38	10	53.8	538				
	554	Con.	N/A		0.171	1.49	5.97	10	59.7	597	554			
	Dickson #2	511	HS1	3	0.107	0.93	3.73	10	37.3	373		137.3	26.9%	
		511	HS1	3	0.108	0.94	3.77	10	37.7	377		133.8	26.2%	
		511	HS1	3	0.113	0.99	3.94	10	39.4	394	382	116.4	22.8%	
		511	CKD	3	0.096	0.84	3.35	10	33.5	335		175.7	34.4%	
		511	CKD	3	0.093	0.81	3.25	10	32.5	325		186.2	36.5%	
		511	CKD	3	0.096	0.84	3.35	10	33.5	335	332	175.7	34.4%	
		511	HS2	3	0.103	0.90	3.60	10	36.0	360		151.3	29.6%	
		511	HS2	3	0.103	0.90	3.60	10	36.0	360		151.3	29.6%	
511		HS2	3	0.103	0.90	3.60	10	36.0	360	360	151.3	29.6%		
511		Red Mud	3	0.112	0.98	3.91	10	39.1	391		119.9	23.5%		
511		Red Mud	3	0.129	1.13	4.50	10	45.0	450		60.5	11.9%		
511		Red Mud	3	0.115	1.00	4.01	10	40.1	401	414	109.4	21.4%		
511		HS1	10	0.100	0.87	3.49	10	34.9	349		161.8	31.7%		
511		HS1	10	0.094	0.82	3.28	10	32.8	328		182.7	35.8%		
511		HS1	10				10				339			
511		CKD	10	0.080	0.70	2.79	10	27.9	279		231.6	45.3%		
511		CKD	10	0.077	0.67	2.69	10	26.9	269		242.0	47.4%		
511		CKD	10	0.082	0.72	2.86	10	28.6	286	278	224.6	44.0%		
511		HS2	10	0.065	0.57	2.27	10	22.7	227		283.9	55.6%		
511		HS2	10	0.063	0.55	2.20	10	22.0	220		290.9	57.0%		
511		HS2	10	0.061	0.53	2.13	10	21.3	213	220	297.9	58.3%		
511		Red Mud	10	0.079	0.69	2.76	10	27.6	276		235.1	46.0%		
511		Red Mud	10	0.074	0.65	2.58	10	25.8	258		252.5	49.4%		
511		Red Mud	10	0.077	0.67	2.69	10	26.9	269	268	242.0	47.4%		
511		Con.	N/A		0.138	1.20	4.82	10	48.2	482				
511		Con.	N/A		0.149	1.30	5.20	10	52.0	520				
511		Con.	N/A		0.152	1.33	5.31	10	53.1	531	511			
Keokuk		296	HS1	3	0.066	0.58	2.30	10	23.0	230		65.1	22.0%	
		296	HS1	3	0.070	0.61	2.44	10	24.4	244		51.2	17.3%	
		296	HS1	3	0.066	0.58	2.30	10	23.0	230	235	65.1	22.0%	
		296	CKD	3	0.082	0.72	2.86	10	28.6	286		9.3	3.1%	
		296	CKD	3	0.075	0.65	2.62	10	26.2	262		33.7	11.4%	
		296	CKD	3				10				274		
		296	HS2	3	0.067	0.58	2.34	10	23.4	234		61.6	20.9%	
		296	HS2	3	0.066	0.58	2.30	10	23.0	230		65.1	22.0%	
	296	HS2	3	0.063	0.55	2.20	10	22.0	220	228	75.6	25.6%		
	296	Red Mud	3	0.065	0.57	2.27	10	22.7	227		68.6	23.2%		
	296	Red Mud	3	0.071	0.62	2.48	10	24.8	248		47.7	16.1%		
	296	Red Mud	3	0.072	0.63	2.51	10	25.1	251	242	44.2	15.0%		
	296	HS1	10	0.054	0.47	1.88	10	18.8	188		107.0	36.2%		
	296	HS1	10	0.053	0.46	1.85	10	18.5	185		110.5	37.4%		
	296	HS1	10	0.048	0.42	1.68	10	16.8	168	180	128.0	43.3%		
	296	CKD	10	0.064	0.56	2.23	10	22.3	223		72.1	24.4%		
	296	CKD	10	0.071	0.62	2.48	10	24.8	248		47.7	16.1%		
	296	CKD	10	0.065	0.57	2.27	10	22.7	227	233	68.6	23.2%		
	296	HS2	10	0.033	0.29	1.15	10	11.5	115		180.3	61.0%		
	296	HS2	10	0.037	0.32	1.29	10	12.9	129		166.4	56.3%		
	296	HS2	10	0.032	0.28	1.12	10	11.2	112	119	183.8	62.2%		
	296	Red Mud	10	0.060	0.52	2.09	10	20.9	209		86.1	29.1%		
	296	Red Mud	10	0.060	0.52	2.09	10	20.9	209		86.1	29.1%		
	296	Red Mud	10	0.060	0.52	2.09	10	20.9	209	242	86.1	29.1%		
	296	con.	N/A		0.084	0.73	2.93	10	29.3	293				
296	con.	N/A		0.083	0.72	2.90	10	29.0	290					
296	con.	N/A		0.087	0.76	3.04	10	30.4	304	296				

Table A5. Incubation study pH changes for 9 week sample time.

9 Weeks							
Soil	initial pH	amend	% amend.	pH	avg.	pH incr.	
Dickson #1	5.3	HS1	3	5.6		0.3	
	5.3	HS1	3	5.6		0.3	
	5.3	HS1	3	5.7	5.6	0.4	
	5.3	CKD	3	7.3		2	
	5.3	CKD	3	7.4		2.1	
	5.3	CKD	3	7.5	7.4	2.2	
	5.3	HS2	3	6.4		1.1	
	5.3	HS2	3	6.5		1.2	
	5.3	HS2	3	6.3	6.4	1	
	5.3	Red Mud	3	6.8		1.5	
	5.3	Red Mud	3	6.8		1.5	
	5.3	Red Mud	3	6.7	6.8	1.4	
	5.3	HS1	10	5.9		0.6	
	5.3	HS1	10	5.7		0.4	
	5.3	HS1	10	5.7	5.8	0.4	
	5.3	CKD	10	8		2.7	
	5.3	CKD	10	8.1		2.8	
	5.3	CKD	10	8.2	8.1	2.9	
	5.3	HS2	10	7.3		2	
	5.3	HS2	10	6.9		1.6	
	5.3	HS2	10	6.9	7.0	1.6	
	5.3	Red Mud	10	7.3		2	
	5.3	Red Mud	10	7.4		2.1	
	5.3	Red Mud	10	7.3	7.3	2	
			Con.	N/A	5.4		
			Con.	N/A	5.2		
			Con.	N/A	5.2	5.3	
	Dickson #2	5.6	HS1	3	5.9		0.3
		5.6	HS1	3	6		0.4
		5.6	HS1	3	5.9	5.9	0.3
		5.6	CKD	3	7.2		1.6
		5.6	CKD	3	7.3		1.7
		5.6	CKD	3	7.3	7.3	1.7
5.6		HS2	3	6.4		0.8	
5.6		HS2	3	6.4		0.8	
5.6		HS2	3	6.3	6.4	0.7	
5.6		Red Mud	3	6.7		1.1	
5.6		Red Mud	3	6.7		1.1	
5.6		Red Mud	3	6.8	6.7	1.2	
5.6		HS1	10	6		0.4	
5.6		HS1	10	6		0.4	
5.6		HS1	10	5.9	6.0	0.3	
5.6		CKD	10	8		2.4	
5.6		CKD	10	8		2.4	
5.6		CKD	10	8	8.0	2.4	
5.6		HS2	10	7.2		1.6	
5.6		HS2	10	7.1		1.5	
5.6		HS2	10	7.1	7.1	1.5	
5.6		Red Mud	10	7.4		1.8	
5.6		Red Mud	10	7.4		1.8	
5.6		Red Mud	10	7.4	7.4	1.8	
			Con.	N/A	5.6		
			Con.	N/A	5.6		
			Con.	N/A	5.6	5.6	
Keokuk	7.9	HS1	3	7.7		-0.2	
	7.9	HS1	3	7.8		-0.1	
	7.9	HS1	3	7.8	7.8	-0.1	
	7.9	CKD	3	8.2		0.3	
	7.9	CKD	3	8.2		0.3	
	7.9	CKD	3	8.1	8.2	0.2	
	7.9	HS2	3	7.8		-0.1	
	7.9	HS2	3	7.8		-0.1	
	7.9	HS2	3	7.8	7.8	-0.1	
	7.9	Red Mud	3	7.8		-0.1	
	7.9	Red Mud	3	7.8		-0.1	
	7.9	Red Mud	3	7.8	7.8	-0.1	
	7.9	HS1	10	7.7		-0.2	
	7.9	HS1	10	7.7		-0.2	
	7.9	HS1	10	7.7	7.7	-0.2	
	7.9	CKD	10	8.3		0.4	
	7.9	CKD	10	8.3		0.4	
	7.9	CKD	10	8.4	8.3	0.5	
	7.9	HS1	10	7.8		-0.1	
	7.9	HS1	10	7.8		-0.1	
	7.9	HS1	10	7.8	7.8	-0.1	
	7.9	Red Mud	10	7.9		0	
	7.9	Red Mud	10	7.9		0	
	7.9	Red Mud	10	7.9	7.9	0	
		Con.	N/A	7.9			
		Con.	N/A	7.8			
		Con.	N/A	7.9	7.9		

Table A6. Incubation study soluble salt (EC) changes for 9 week sample time.

9 Weeks						
Soil	Initial EC	amend	% amend	EC	avg.	EC inc/dec
Dickson #1	0.163	HS1	3	0.061		
	0.163	HS1	3	0.067		
	0.163	HS1	3	0.062	0.063	-0.100
	0.163	CKD	3	0.256		
	0.163	CKD	3	0.235		
	0.163	.CKD	3	0.275	0.255	0.092
	0.163	HS2	3	0.115		
	0.163	HS2	3	0.093		
	0.163	HS2	3	0.102	0.103	-0.060
	0.163	Red Mud	3	0.239		
	0.163	Red Mud	3	0.213		
	0.163	Red Mud	3	0.302	0.251	0.088
	0.163	HS1	10	0.119		
	0.163	HS1	10	0.185		
	0.163	HS1	10	0.183	0.162	-0.001
	0.163	CKD	10	0.571		
	0.163	CKD	10	0.634		
	0.163	CKD	10	0.505	0.570	0.407
	0.163	HS2	10	0.196		
	0.163	HS2	10	0.115		
	0.163	HS2	10	0.191	0.167	0.004
	0.163	Red Mud	10	0.491		
	0.163	Red Mud	10	0.514		
	0.163	Red Mud	10	0.608	0.538	0.375
	0.163	Con.	N/A	0.163		
	0.163	Con.	N/A	0.181		
	0.163	Con.	N/A	0.144	0.163	N/A
Dickson #2	0.338	HS1	3	0.25		
	0.338	HS1	3	0.21		
	0.338	HS1	3	0.219	0.226	-0.112
	0.338	CKD	3	0.298		
	0.338	CKD	3	0.327		
	0.338	CKD	3	0.256	0.294	-0.044
	0.338	HS2	3	0.139		
	0.338	HS2	3	0.222		
	0.338	HS2	3	0.212	0.191	-0.147
	0.338	Red Mud	3	0.315		
	0.338	Red Mud	3	0.297		
	0.338	Red Mud	3	0.376	0.329	-0.009
	0.338	HS1	10	0.318		
	0.338	HS1	10	0.272		
	0.338	HS1	10	0.241	0.277	-0.061
	0.338	CKD	10	0.685		
	0.338	CKD	10	0.897		
	0.338	CKD	10	0.693	0.758	0.420
	0.338	HS2	10	0.289		
	0.338	HS2	10	0.202		
	0.338	HS2	10	0.277	0.256	-0.082
	0.338	Red Mud	10	0.455		
	0.338	Red Mud	10	0.409		
	0.338	Red Mud	10	0.567	0.477	0.139
	0.338	Con.	N/A	0.366		
	0.338	Con.	N/A	0.292		
	0.338	Con.	N/A	0.355	0.338	N/A
Keokuk	0.366	HS1	3	0.305		
	0.366	HS1	3	0.296		
	0.366	HS1	3	0.237	0.279	-0.087
	0.366	CKD	3	0.325		
	0.366	CKD	3	0.468		
	0.366	CKD	3	0.419	0.404	0.038
	0.366	HS2	3	0.437		
	0.366	HS2	3	0.314		
	0.366	HS2	3	0.254	0.335	-0.031
	0.366	Red Mud	3	0.495		
	0.366	Red Mud	3	0.692		
	0.366	Red Mud	3	0.494	0.560	0.194
	0.366	HS1	10	0.357		
	0.366	HS1	10	0.439		
	0.366	HS1	10	0.453	0.416	0.050
	0.366	CKD	10	0.52		
	0.366	CKD	10	0.626		
	0.366	CKD	10	0.957	0.701	0.335
	0.366	HS1	10	0.484		
	0.366	HS1	10	0.289		
	0.366	HS1	10	0.441	0.405	0.039
	0.366	Red Mud	10	0.665		
	0.366	Red Mud	10	0.616		
	0.366	Red Mud	10	0.754	0.678	0.312
	0.366	Con.	N/A	0.392		
	0.366	Con.	N/A	0.325		
	0.366	Con.	N/A	0.38	0.366	N/A

Table A7. Incubation study soluble P reduction for 9 week sample time.

9 Weeks													
Soil	CaCl <sub>2</sub> soil ppm	amend	% amend.	abs.	ug in 1.0	dil extract ug/mL	dil factor	extract ug/mL	CaCl <sub>2</sub> soil ppm	CaCl <sub>2</sub> avg.	reduction in ug/mL	% removed	
Dickson #1	67.5	HS1	3	0.156	1.36	1.36	1	1.4	13.6		53.9	79.8%	
	67.5	HS1	3	0.127	1.11	1.11	1	1.1	11.1		56.4	83.6%	
	67.5	HS1	3	0.106	0.92	0.92	1	0.9	9.2	11.3	58.3	86.3%	
	67.5	CKD	3	0.229	2.00	2.00	1	2.0	20.0		47.5	70.4%	
	67.5	CKD	3	0.222	1.94	1.94	1	1.9	19.4		48.1	71.3%	
	67.5	CKD	3	0.229	2.00	2.00	1	2.0	20.0		47.5	70.4%	
	67.5	HS2	3	0.056	0.49	0.49	1	0.5	4.9		62.6	92.8%	
	67.5	HS2	3	0.056	0.49	0.49	1	0.5	4.9		62.6	92.8%	
	67.5	HS2	3	0.053	0.46	0.46	1	0.5	4.6	4.8	62.9	93.1%	
	67.5	Red Mud	3	0.204	1.78	1.78	1	1.8	17.8		49.7	73.6%	
	67.5	Red Mud	3	0.200	1.75	1.75	1	1.7	17.5		50.0	74.1%	
	67.5	Red Mud	3	0.215	1.88	1.88	1	1.9	18.8	18.0	48.7	72.2%	
	67.5	HS1	10	0.030	0.26	0.26	1	0.3	2.6		64.9	96.1%	
	67.5	HS1	10	0.031	0.27	0.27	1	0.3	2.7		64.8	96.0%	
	67.5	HS1	10	0.037	0.32	0.32	1	0.3	3.2	2.9	64.3	95.2%	
	67.5	CKD	10	0.118	1.03	1.03	1	1.0	10.3		57.2	84.7%	
	67.5	CKD	10	0.122	1.06	1.06	1	1.1	10.6		56.9	84.2%	
	67.5	CKD	10	0.125	1.09	1.09	1	1.1	10.9	10.6	56.6	83.8%	
	67.5	HS2	10	0.016	0.14	0.14	1	0.1	1.4		66.1	97.9%	
	67.5	HS2	10	0.021	0.18	0.18	1	0.2	1.8		65.7	97.3%	
	67.5	HS2	10	0.018	0.16	0.16	1	0.2	1.6	1.6	65.9	97.7%	
	67.5	Red Mud	10	0.140	1.22	1.22	1	1.2	12.2		55.3	81.9%	
	67.5	Red Mud	10	0.140	1.22	1.22	1	1.2	12.2		55.3	81.9%	
	67.5	Red Mud	10	0.141	1.23	1.23	1	1.2	12.3	12.2	55.2	81.8%	
			Con.	N/A	0.080	0.70	0.70	10	7.0	69.8			
			Con.	N/A	0.079	0.69	0.69	10	6.9	68.9			
			Con.	N/A	0.073	0.64	0.64	10	6.4	63.7	67.5		
	Dickson #2	75.9	HS1	3	0.114	0.99	0.99	1	1.0	9.9		66.0	86.9%
		75.9	HS1	3	0.103	0.90	0.90	1	0.9	9.0		66.9	88.2%
		75.9	HS1	3	0.083	0.72	0.72	1	0.7	7.2	8.7	68.7	90.5%
		75.9	CKD	3	0.204	1.78	1.78	1	1.8	17.8		58.1	76.5%
		75.9	CKD	3	0.256	2.23	2.23	1	2.2	22.3		53.6	70.6%
		75.9	CKD	3	0.218	1.90	1.90	1	1.9	19.0	19.7	56.9	74.9%
		75.9	HS2	3	0.043	0.38	0.38	1	0.4	3.8		72.1	95.1%
		75.9	HS2	3	0.044	0.38	0.38	1	0.4	3.8		72.1	94.9%
		75.9	HS2	3	0.055	0.48	0.48	1	0.5	4.8	4.1	71.1	93.7%
75.9		Red Mud	3	0.000	0.00	0.00	1	0.0	0.0		0.0	00.0%	
75.9		Red Mud	3	0.208	1.82	1.82	1	1.8	18.2		57.7	76.1%	
75.9		Red Mud	3	0.195	1.70	1.70	1	1.7	17.0	17.6	58.9	77.6%	
75.9		HS1	10	0.031	0.27	0.27	1	0.3	2.7		73.2	96.4%	
75.9		HS1	10	0.030	0.26	0.26	1	0.3	2.6		73.3	96.6%	
75.9		HS1	10	0.033	0.29	0.29	1	0.3	2.9	2.7	73.0	96.2%	
75.9		CKD	10	0.121	1.06	1.06	1	1.1	10.6		65.3	86.1%	
75.9		CKD	10	0.116	1.01	1.01	1	1.0	10.1		65.8	86.7%	
75.9		CKD	10	0.119	1.04	1.04	1	1.0	10.4	10.4	65.5	86.3%	
75.9		HS2	10	0.010	0.09	0.09	1	0.1	0.9		75.0	98.9%	
75.9		HS2	10	0.009	0.08	0.08	1	0.1	0.8		75.1	99.0%	
75.9		HS2	10	0.009	0.08	0.08	1	0.1	0.8	0.8	75.1	99.0%	
75.9		Red Mud	10	0.108	0.94	0.94	1	0.9	9.4		66.5	87.6%	
75.9		Red Mud	10	0.117	1.02	1.02	1	1.0	10.2		65.7	86.5%	
75.9		Red Mud	10	0.112	0.98	0.98	1	1.0	9.8	9.8	66.1	87.1%	
			Con.	N/A	0.084	0.73	0.73	10	7.3	73.3			
			Con.	N/A	0.093	0.81	0.81	10	8.1	81.2			
			Con.	N/A	0.084	0.73	0.73	10	7.3	73.3	75.9		
Keokuk		20.4	HS1	3	0.080	0.70	0.70	1	0.7	7.0		13.4	65.8%
		20.4	HS1	3	0.073	0.64	0.64	1	0.6	6.4		14.0	68.8%
		20.4	HS1	3	0.042	0.37	0.37	1	0.4	3.7	5.7	16.7	82.0%
		20.4	CKD	3	0.140	1.22	1.22	1	1.2	12.2		8.2	40.1%
		20.4	CKD	3	0.118	1.03	1.03	1	1.0	10.3		10.1	49.5%
		20.4	CKD	3	0.145	1.27	1.27	1	1.3	12.7	11.7	7.7	38.0%
		20.4	HS2	3	0.042	0.37	0.37	1	0.4	3.7		16.7	82.0%
		20.4	HS2	3	0.045	0.39	0.39	1	0.4	3.9		16.5	80.8%
		20.4	HS2	3	0.037	0.32	0.32	1	0.3	3.2	3.6	17.2	84.2%
	20.4	Red Mud	3	0.149	1.30	1.30	1	1.3	13.0		7.4	36.3%	
	20.4	Red Mud	3	0.180	1.57	1.57	1	1.6	15.7		4.7	23.0%	
	20.4	Red Mud	3	0.199	1.74	1.74	1	1.7	17.4	15.4	3.0	14.9%	
	20.4	HS1	10	0.019	0.17	0.17	1	0.2	1.7		18.7	91.9%	
	20.4	HS1	10	0.020	0.17	0.17	1	0.2	1.7		18.7	91.4%	
	20.4	HS1	10	0.013	0.11	0.11	1	0.1	1.1	1.5	19.3	94.4%	
	20.4	CKD	10	0.062	0.54	0.54	1	0.5	5.4		15.0	73.5%	
	20.4	CKD	10	0.058	0.51	0.51	1	0.5	5.1		15.3	75.2%	
	20.4	CKD	10	0.058	0.51	0.51	1	0.5	5.1	5.2	15.3	75.2%	
	20.4	HS2	10	0.096	0.84	0.84	1	0.8	8.4		12.0	58.9%	
	20.4	HS2	10	0.024	0.21	0.21	1	0.2	2.1		18.3	89.7%	
	20.4	HS2	10	0.000	0.00	0.00	1	0.0	0.0	5.2	0.0	00.0%	
	20.4	Red Mud	10	0.097	0.85	0.85	1	0.8	8.5		11.9	58.5%	
	20.4	Red Mud	10	0.000	0.00	0.00	1	0.0	0.0		0.0	00.0%	
	20.4	Red Mud	10	0.098	0.86	0.86	1	0.9	8.6	8.5	11.8	58.1%	
			Con.	N/A	0.023	0.20	0.20	10	2.0	20.1			
			Con.	N/A	0.023	0.20	0.20	10	2.0	20.1			
			Con.	N/A	0.024	0.21	0.21	10	2.1	20.9	20.4		

Table A8. Incubation study KCl extractable AI totals for 9 week sample time.

Soil	Amend.	Rate	Rep	KCl AI	Avg. AI	
Dickson #1	HS1	3	1	12.7	14.3	
	HS1	3	2	15.9		
	HS1	10	1	7.47	5.42	
	HS1	10	2	3.36		
	CKD	3	1	1.57	1.45	
	CKD	3	2	1.32		
	CKD	10	1	1.36	1.49	
	CKD	10	2	1.62		
	HS2	3	1	0.94	2.84	
	HS2	3	2	4.74		
	HS2	10	1	4.57	3.94	
	HS2	10	2	3.31		
	Red Mud	3	1	1.64	1.57	
	Red Mud	3	2	1.50		
	Red Mud	10	1	0.89	0.78	
	Red Mud	10	2	0.67		
	Dickson #2	CON	0	1	1.51	1.87
		CON	0	2	2.23	
HS1		3	1	2.38	1.95	
HS1		3	2	1.52		
HS1		10	1	1.08	0.99	
HS1		10	2	0.89		
CKD		3	1	1.00	1.21	
CKD		3	2	1.42		
CKD		10	1	1.29	1.22	
CKD		10	2	1.16		
HS2		3	1	1.14	1.27	
HS2		3	2	1.40		
HS2		10	1	0.90	0.89	
HS2		10	2	0.88		
Red Mud		3	1	3.22	5.82	
Red Mud		3	2	8.42		
Red Mud		10	1	2.15	1.55	
Red Mud		10	2	0.96		
Keokuk	CON	0	1	0.82	1.18	
	CON	0	2	1.54		
	HS1	3	1	1.37	1.67	
	HS1	3	2	1.97		
	HS1	10	1	3.45	4.22	
	HS1	10	2	4.98		
	CKD	3	1	0.42	0.97	
	CKD	3	2	1.51		
	CKD	10	1	0.47	0.38	
	CKD	10	2	0.28		
	HS2	3	1	0.70	1.20	
	HS2	3	2	1.70		
	HS2	10	1	1.23	1.19	
	HS2	10	2	1.16		
	Red Mud	3	1	0.00	0.52	
	Red Mud	3	2	1.04		
	Red Mud	10	1	0.74	0.56	
	Red Mud	10	2	0.39		
CON	0	1	0.88	1.03		
CON	0	2	1.18			

Table A9. Greenhouse runoff study soluble P reduction data.

amend.	type	box	abs.	ug in 0.25	dil extract ug/mL	sol. P avg.
n/a	bkg	4	0.020	0.21	0.848	
			0.011	0.117	0.467	0.657
n/a	bkg	23	0.009	0.095	0.382	
			0.019	0.201	0.806	0.594
n/a	bkg	26	0.010	0.106	0.424	
			0.007	0.074	0.297	0.361
n/a	bkg	30	0.036	0.382	1.53	
			0.031	0.329	1.31	1.42
0.5 kg HS2	buffer	9	0.308	3.27	13.1	
			0.316	3.35	13.4	13.2
0.5 kg HS2	broad	5	0.364	3.86	15.4	
			0.368	3.90	15.6	15.5
1.0 kg HS2	buffer	16	0.183	1.94	7.76	
			0.193	2.05	8.19	7.97
1.0 kg HS2	broad	13	0.254	2.69	10.8	
			0.262	2.78	11.1	10.9
n/a	con	3	0.513	5.44	21.8	
			0.483	5.12	20.5	21.1
n/a	con	7	0.604	6.41	25.6	
			0.571	6.06	24.2	24.9
n/a	con	29	0.490	5.20	20.8	
			0.494	5.24	21.0	20.9
n/a	bkg	3	0.021	0.223	0.891	
			0.017	0.180	0.721	0.806
n/a	bkg	7	0.028	0.297	1.19	
			0.027	0.286	1.15	1.17
n/a	bkg	29	0.021	0.223	0.891	
			0.023	0.244	0.976	0.933
HS1	buffer	3	0.154	1.63	6.53	
			0.160	1.70	6.79	6.66
HS1	buffer	8	0.187	1.98	7.93	
			0.170	1.80	7.21	7.57
HS1	buffer	19	0.306	3.24	13.0	
			0.294	3.12	12.5	12.7
HS1	broad	7	0.378	4.01	16.0	
			0.402	4.26	17.1	16.5
HS1	broad	23	0.249	2.64	10.6	
			0.248	2.63	10.5	10.5
HS1	broad	28	0.292	3.10	12.4	
			0.275	2.92	11.7	12.0
HS2	buffer	4	0.092	0.976	3.90	
			0.066	0.700	2.80	3.35
HS2	buffer	17	0.204	2.16	8.65	
			0.198	2.10	8.40	8.53
HS2	buffer	27	0.071	0.753	3.01	
			0.066	0.700	2.80	2.91
HS2	broad	11	0.196	2.08	8.31	
			0.200	2.12	8.48	8.40
HS2	broad	26	0.249	2.64	10.6	
			0.249	2.64	10.6	10.6
HS2	broad	29	0.252	2.67	10.7	
			0.245	2.60	10.4	10.5

Table A10. Greenhouse runoff study total P reduction data.

amend.	type	box	rep.	abs.	ug in 0.25	dil extract ug/mL	dil factor	Total P ug/mL	Total P average
n/a	bkg	4	1	0.017	0.180	0.721	1.6	1.2	
			2	0.011	0.117	0.467	1.6	0.7	1.0
n/a	bkg	23	1	0.012	0.127	0.509	1.6	0.8	
			2	0.014	0.148	0.594	1.6	1.0	0.9
n/a	bkg	26	1	0.010	0.106	0.424	1.6	0.7	
			2	0.010	0.106	0.424	1.6	0.7	0.7
n/a	bkg	30	1	0.024	0.25	1.02	1.6	1.6	
			2	0.021	0.223	0.891	1.6	1.4	1.5
0.5 kg HS2	buffer	9	1	0.200	2.12	8.48	1.6	13.6	
			2	0.184	1.95	7.80	1.6	12.5	13.0
0.5 kg HS2	broad	5	1	0.199	2.11	8.44	1.6	13.5	
			2	0.206	2.18	8.74	1.6	14.0	13.7
1.0 kg HS2	buffer	16	1	0.120	1.27	5.09	1.6	8.1	
			2	0.111	1.18	4.71	1.6	7.5	7.8
1.0 kg HS2	broad	13	1	0.148	1.57	6.28	1.6	10.0	
			2	0.149	1.58	6.32	1.6	10.1	10.1
n/a	con	3	1	0.307	3.26	13.0	1.6	20.8	
			2	0.308	3.27	13.1	1.6	20.9	20.9
n/a	con	7	1	0.320	3.39	13.6	1.6	21.7	
			2	0.340	3.61	14.4	1.6	23.1	22.4
n/a	con	29	1	0.288	3.05	12.2	1.6	19.5	
			2	0.279	2.96	11.8	1.6	18.9	19.2
n/a	bkg	3	1	0.020	0.212	0.848	1.6	1.4	
			2	0.023	0.244	0.976	1.6	1.6	1.5
n/a	bkg	7	1	0.030	0.318	1.27	1.6	2.0	
			2	0.022	0.233	0.933	1.6	1.5	1.8
n/a	bkg	29	1	0.021	0.223	0.891	1.6	1.4	
			2	0.021	0.223	0.891	1.6	1.4	1.4
HS1	buffer	3	1	0.095	1.01	4.03	1.6	6.4	
			2	0.098	1.04	4.16	1.6	6.7	6.5
HS1	buffer	8	1	0.109	1.16	4.62	1.6	7.4	
			2	0.120	1.27	5.09	1.6	8.1	7.8
HS1	buffer	19	1	0.197	2.09	8.36	1.6	13.4	
			2	0.157	1.66	6.66	1.6	10.7	12.0
HS1	broad	7	1	0.225	2.39	9.54	1.6	15.3	
			2	0.237	2.51	10.1	1.6	16.1	15.7
HS1	broad	23	1	0.169	1.79	7.17	1.6	11.5	
			2	0.163	1.73	6.91	1.6	11.1	11.3
HS1	broad	28	1	0.170	1.80	7.21	1.6	11.5	
			2	0.171	1.81	7.25	1.6	11.6	11.6
HS2	buffer	4	1	0.051	0.541	2.16	1.6	3.5	
			2	0.053	0.562	2.25	1.6	3.6	3.5
HS2	buffer	17	1	0.125	1.33	5.30	1.6	8.5	
			2	0.129	1.37	5.47	1.6	8.8	8.6
HS2	buffer	27	1	0.053	0.562	2.25	1.6	3.6	
			2	0.049	0.520	2.08	1.6	3.3	3.5
HS2	broad	11	1	0.122	1.29	5.17	1.6	8.3	
			2	0.134	1.42	5.68	1.6	9.1	8.7
HS2	broad	26	1	0.150	1.59	6.36	1.6	10.2	
			2	0.154	1.63	6.53	1.6	10.5	10.3
HS2	broad	29	1	0.154	1.63	6.53	1.6	10.5	
			2	0.159	1.69	6.74	1.6	10.8	10.6



Table A11. Percent cover and forage yield of all fescue boxes.

Treatment	Box #	Blade	Debris	Ground	Forage Yield
		%	%	%	kg/ha
HS2 buffer	4	25	50	25	4129
HS1 buffer	8	50	25	25	2757
HS2 broad	11	20	45	35	2553
HS2 buffer	17	25	55	20	6495
HS1 buffer	19	20	35	45	3947
HS1 broad	23	20	50	30	2804
HS2 broad	26	35	40	25	2765
HS2 buffer	27	25	65	10	1929
HS1 broad	28	15	40	45	4056

Table A12. Kinetics study of hydrosolids.

Amend	Time	abs.	ug in 0.25	dil extract ug/mL	dil factor	extract ug/mL
HS1	0.5	0.340	3.61	14.4	10.00	144
	1	0.281	2.98	11.9	10	119
	3	0.277	2.94	11.7	10	117
	5	0.264	2.80	11.2	10	112
	10	0.206	2.18	8.74	10	87.4
	20	0.258	2.74	10.9	10	109
	25	0.257	2.73	10.9	10	109
	30	0.233	2.47	9.88	10	98.8
	45	0.235	2.49	9.97	10	99.7
	60	0.207	2.20	8.78	10	87.8
	90	0.192	2.04	8.14	10	81.4
	120	0.177	1.88	7.51	10	75.1
	150	0.160	1.70	6.79	10	67.9
	180	0.149	1.58	6.32	10	63.2
	300	0.121	1.28	5.13	10	51.3
	420	0.101	1.07	4.28	10	42.8
	600	0.771	8.18	32.7	1	32.7
	900	0.537	5.69	22.8	1	22.8
	1500	0.247	2.62	10.5	1	10.5
	1800	0.200	2.12	8.48	1	8.48
2100	0.226	2.40	9.59	1	9.59	
2400	0.170	1.80	7.21	1	7.21	
3000	0.134	1.42	5.68	1	5.68	
3300	0.119	1.26	5.05	1	5.05	
HS2 Coarse	0.5	0.309	3.28	13.1	10	131
	1	0.281	2.98	11.9	10	119
	3	0.273	2.90	11.6	10	116
	5	0.266	2.82	11.3	10	113
	10	0.252	2.67	10.7	10	107
	20	0.240	2.55	10.2	10	102
	25	0.225	2.39	9.54	10	95.4
	30	0.209	2.22	8.87	10	88.7
	45	0.190	2.01	8.06	10	80.6
	60	0.166	1.76	7.04	10	70.4
	90	0.130	1.38	5.51	10	55.1
	120	0.109	1.16	4.62	10	46.2
	150	0.087	0.923	3.69	10	36.9
	180	0.076	0.806	3.22	10	32.2
	300	0.038	0.403	1.61	10	16.1
	420	0.021	0.223	0.891	10	8.91
	600	0.066	0.700	2.80	1	2.80
900	0.014	0.148	0.594	1	0.59	
1500	0.001	0.011	0.042	1	0.04	
1800	0.000	0.000	0.000	1	0.00	
HS2 Fine	0.5	0.969	10.3	41.1	1	41.1
	1	0.906	9.61	38.4	1	38.4
	3	0.847	8.98	35.9	1	35.9
	5	0.766	8.12	32.5	1	32.5
	10	0.578	6.13	24.5	1	24.5
	20	0.369	3.91	15.7	1	15.7
	25	0.292	3.10	12.4	1	12.4
	30	0.208	2.21	8.82	1	8.82
	45	0.132	1.40	5.60	1	5.60
	60	0.088	0.933	3.73	1	3.73
	90	0.050	0.530	2.12	1	2.12
	120	0.043	0.456	1.82	1	1.82
	150	0.030	0.318	1.27	1	1.27
	180	0.022	0.233	0.933	1	0.933
	300	0.008	0.085	0.339	1	0.339
420	0.004	0.042	0.170	1	0.170	
600	0.001	0.011	0.042	1	0.042	
900	0.000	0.000	0.000	1	0.000	

Figure A1. Runoff hydrographs for Hydrosolid #1 broadcast treatment.

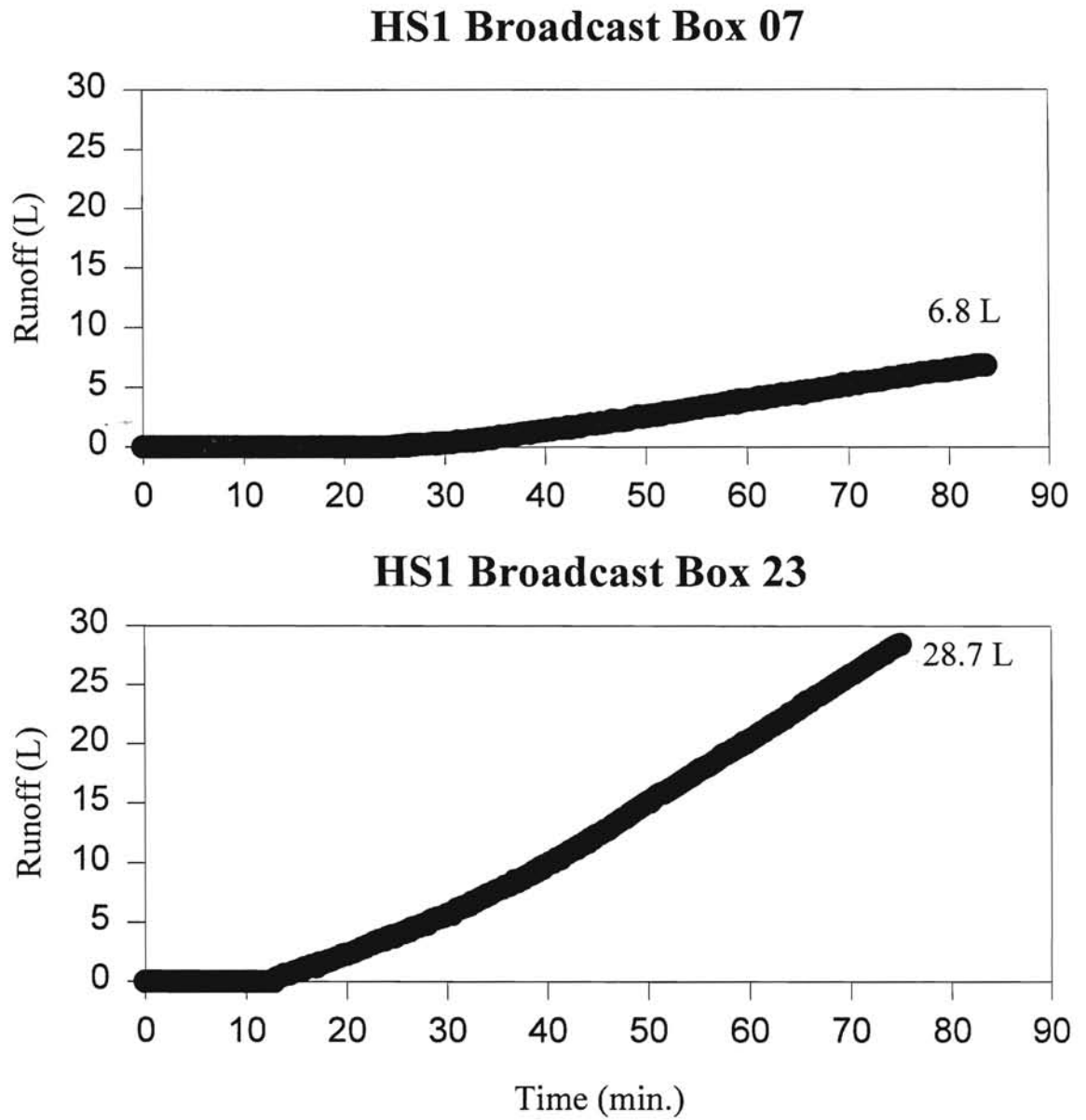


Figure A2. Runoff hydrographs for Hydrosolid #1 buffer strip treatment.

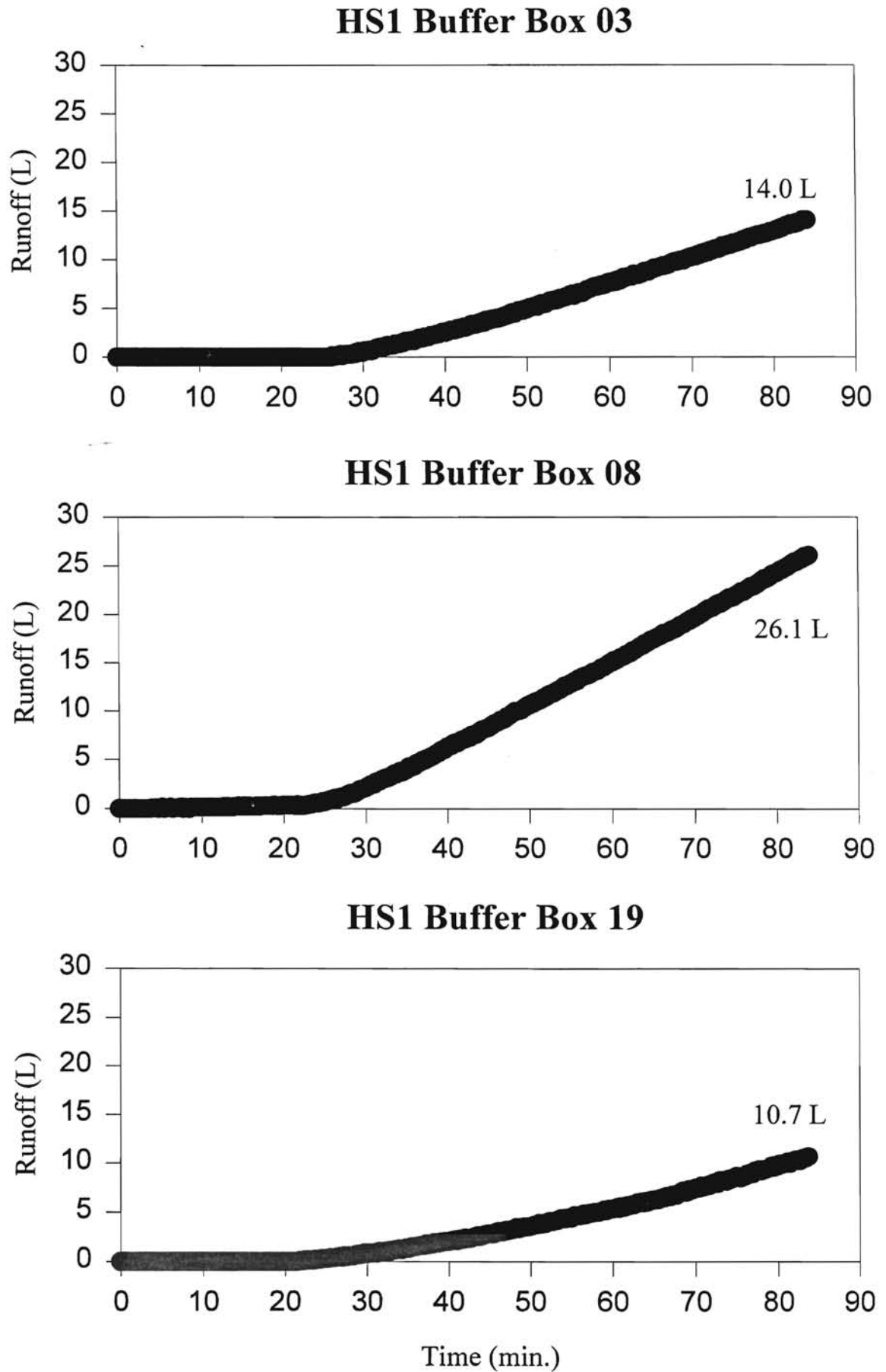
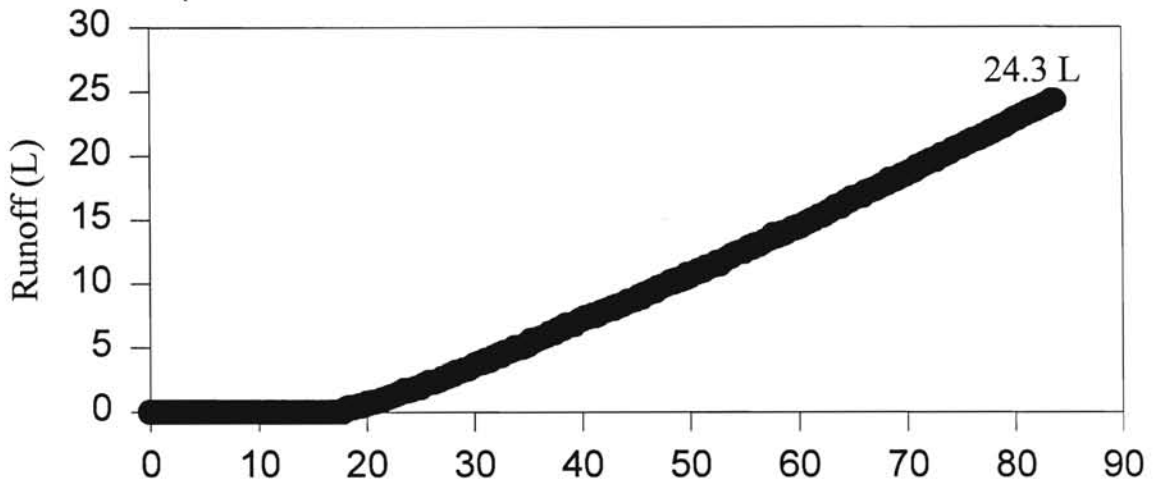
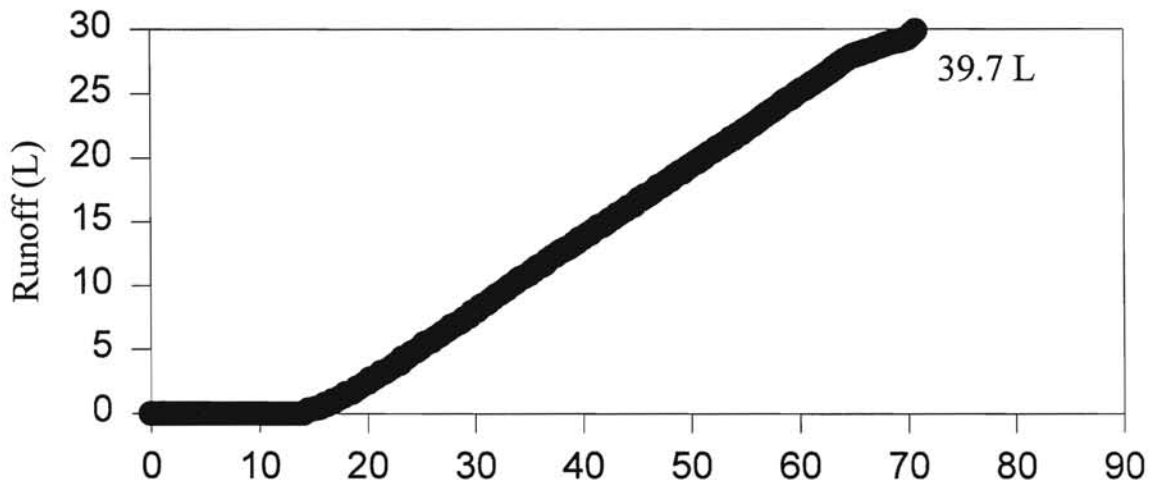


Figure A3. Runoff hydrographs for Hydrosolid #2 broadcast treatment.

### HS2 Broadcast Box 11



### HS2 Broadcast Box 26



### HS2 Broadcast Box 29

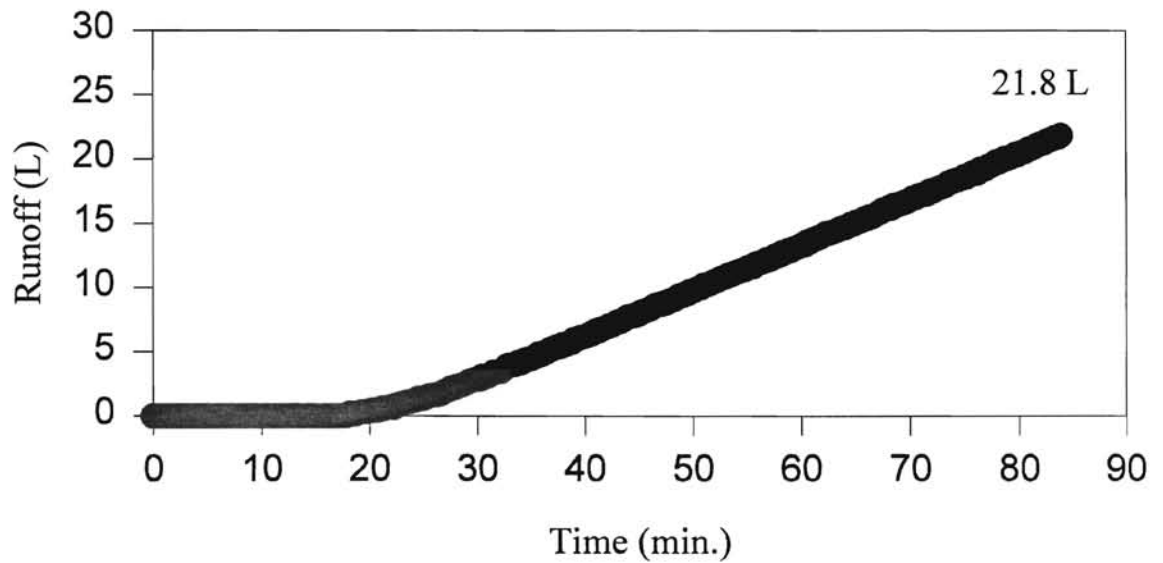
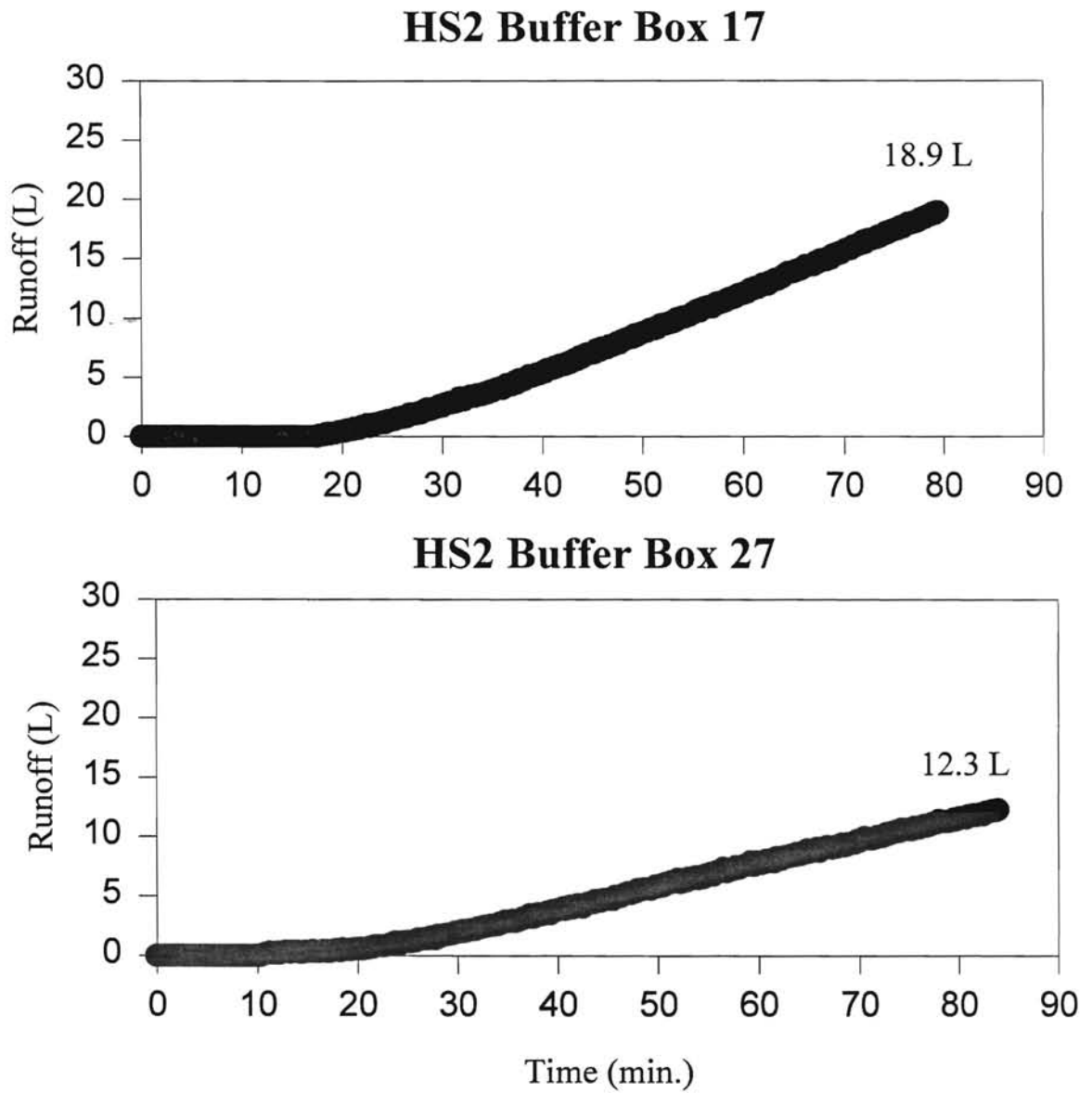


Figure A4. Runoff hydrographs for Hydrosolid #2 buffer strip treatment.



## VITA

Jason Michael Peters

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Master of Science

Thesis: USE OF MUNICIPAL AND INDUSTRIAL WASTE AMENDMENTS  
TO REDUCE BIOAVAILABLE PHOSPHORUS FROM  
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