Management of Alum-Treated Poultry Litter

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Abstract

Previous research has shown that treatment of poultry litter with alum is an effective management strategy to reduce phosphorus (P) solubility in litter thereby reducing potential P losses to surface runoff after surface applications. However, limited data are available evaluating alum-treated poultry litter (ATPL) environmental impact in cultivated systems and how its application will affect crop production. In addition little is known as to how its application affects various P fractions or exchangeable Aluminum (Al) content in treated soils. Two, 3-yr field trials with corn (*Zea mays* L.) were used to show that, when applied at rates based on current litter management strategies, ATPL resulted in yields similar to those achieved through applications of non-treated poultry litter (NPL). These trials also showed that ATPL applications resulted in lower soil P status and decreased P losses in surface water runoff compared to application of NPL. A 4-yr field trial with fescue (*Festuca arudinacea*) also showed no significant differences in productivity when comparing ATPL and NPL. This trial was utilized to evaluate the distribution of P in soils receiving ATPL. Soil analysis data showed that ATPL applications result in decreased water-extractable P (H_2O-P) and that this decrease was associated with an elevation in NaOH extractable organic soil P. A laboratory incubation was utilized to evaluate the short and long-term impact of ATPL application on soil pH, exchangeable soil Al and H_2O-P. Data from this incubation confirmed that the relationship between soil pH and exchangeable Al is not adversely affected by ATPL applications. Also, variations in the H_2O-P content of soils treated with two different ATPL sources could not be associated with differences in Al:P ratio or soluble P content of the two litters, providing evidence that additional characteristics also control P availability after incorporation in soil.

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Chapter 1: Introduction

Phosphorus (P) is often cited as the limiting nutrient for accelerated eutrophication of surface water bodies. The process of eutrophication results in various adverse impacts on surface water quality. These changes in surface water quality result from increased primary productivity such as increased phytoplankton growth and shifts in phytoplankton to bloom-forming species (Carpenter et al., 1998). Eutrophic conditions can also result in the outbreak of toxic dinoflagulates such as *Pfiesteria* spp. (Burkholder and Glasgow, 1997). Eutrophication results in decreased water clarity, dissolved oxygen concentrations and esthetic value of surface waters in addition to causing adverse changes in the smell and taste of water which result in increased drinking water treatment costs (Carpenter et al., 1998).

Inputs of P to surface water bodies come primarily from non-point sources originating from various land uses such as urban, forest and agricultural uses. A significant portion of this P comes from agricultural activities. Phosphorus applications to agricultural lands are required to optimize crop production. However, applications in excess of crop requirement and/or crop removal result in a buildup of excessive levels of P in agricultural soils. Excessive P in agricultural soils has been linked to elevated concentrations of P in surface water runoff (Sharpley, 1995; Pote et al., 1996). Phosphorus applications in excess of crop requirement have historically occurred due to long-term applications of animal manures such as poultry (*Gallus gallus domesticus*) litter to agricultural fields near animal production facilities. This has occurred because animal manures such as poultry litter were historically applied at rates sufficient to supply adequate nitrogen (N) for crop growth. The N to P ratio found in poultry litter ranges from 0.6 to 1.0 (Evanylo and Mullins, 2000), however, the N to P ratio in agronomic crops can range from 2.0 in cotton (*Gossypium hirsutum* L.) to 9.0 in peanuts (*Arachis hypogaea* L.) (Donohue, 2000). This imbalance has resulted in elevated soil P concentrations when litter has been managed as a source of N.

Currently, poultry litter management strategies have shifted from N-based strategies to P-based strategies. These strategies are designed to reduce the potential loss of P to surface water bodies resulting from land application of poultry litter. A management tool used to accomplish this is the P site index. The P site index developed for use in Virginia evaluates the P transport, source and management factors that control P losses to surface water bodies (Mullins et al., 2005). The source component of the P site index accounts for not only the rate of P applied but also the solubility of P contained in the P source. Therefore, the rate of P application can be reduced or the solubility of P found in a P source such as poultry litter can be reduced to ensure decreased P transport to surface water bodies. Decreased application rates will require increased land area for application and subsequent increases in the costs associated with poultry litter transport. Also, decreased application rates under P-based management increase the need for supplemental inorganic N applications for crop production near concentrated areas of poultry production. An alternative to decreased application rates is chemical alteration of poultry litter to reduce the solubility of P in litter. Decreased P solubility in poultry litter has the potential to minimize the impact of its application on surface water P concentrations while at the same time allowing for the utilization of poultry litter N for crop production.

Use of Alum to Reduce P Solubility in Poultry Litter

Various compounds have been evaluated for their effectiveness in reducing the solubility of P in poultry litter (Shreve et al., 1996; Moore and Miller, 1994). However, alum ($Al_2(SO_4)_3 \bullet 16H_2O$) has been found to be one of the most cost effective options (Moore et al., 1999). Initial laboratory evaluation of alum as a poultry litter amendment revealed that additions of alum at rates of 100 g kg^{-1} could reduce the concentration of soluble P by 75% (Moore and Miller, 1994; Shreve et al., 1996). A subsequent farm-scale evaluation of alum as a litter amendment confirmed these findings (Sims and Luka-McCafferty, 2002). Sims and Luka-McCafferty (2002) applied alum to 97 houses at the recommended rate of 0.09 kg alum m^{-2} flock^{-1}. This rate was estimated to be equivalent to that required to result in a final litter containing 10% alum by weight if previous litter was not present in the house at the time of application (Moore et al., 1999). However, the houses included in the study of Sims and Luka-McCafferty (2002) varied widely in the amount of litter present at the initiation of the study. Therefore the Al:P ratio varied dramatically from 0.14 to 1.13 with an average of 0.57. Despite this variation, applications of alum resulted in an average decrease in soluble P of 72% compared to that in litter collected from 97 poultry houses not receiving the alum treatment. In fact, Sims and Luka-McCafferty (2002) showed only minor changes in the solubility of P and other heavy metal constituents in litter receiving alum as the Al:P ratio increased from 0.2 to 1.0. This was contradictory to previous recommendations that required alum additions sufficient to result in an Al:P ratio of 1.0 for optimum precipitation of soluble P in litter (Moore et al., 1999).

Studies focusing on evaluating the mechanisms by which this reduction in P solubility, due to alum treatment of poultry litter, is achieved have recently been presented. X-ray adsorption near edge structure spectroscopy analysis was used to determine that in non-treated poultry litter (NPL), P is present as weakly bound inorganic and organic P with some Ca phosphate compounds present (Peak et al., 2002). Analysis of ATPL suggested that alum applied to the litter precipitates as amorphous $Al(OH)_3$ to which inorganic P was adsorbed. Further investigation into the speciation of P in poultry litter using solid-state ^{31}P nuclear magnetic resonance (NMR) spectroscopic analysis found the presence of a complex mixture of organic and inorganic orthophosphates (Hunger et al., 2004). This analysis again revealed a Ca-P phase, which the researchers attributed to surface precipitate on $CaCO_3$ in both ATPL and NPL. They also again found P associated with Al only in the ATPL and stated that this was likely a mixture of poorly ordered wavellite and surface complexes with $Al(OH)_3$.

Impact of ATPL Applications on Surface Runoff P

The reduction in soluble P concentrations in ATPL has been shown to result in decreased concentrations of dissolved reactive P (DRP) in runoff P concentrations surface application. Smith et al. (2004) found that ATPL applications resulted in 47 to 74 % reductions in soluble P concentrations in runoff compared to NPL depending on dietary treatment. Alum treated poultry litter applications also resulted in 63 to 87% reductions in P concentrations in runoff compared to NPL when applied to fescue (*Festuca arundinacea* L) pasture (Shreve et al., 1995). A 3-year, small watershed (0.405

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ha) study showed that annual applications of ATPL to tall fescue would result in 73% lower concentrations of DRP in runoff compared to that from fields receiving NPL (Moore et al., 2000).

Additional Benefits of Alum

In addition to reduced P solubility, alum, when applied to the floor of production houses prior to the addition of each flock of birds, reduces NH_3 volatilization from poultry litter (Moore et al., 2000). This decrease in NH_3 volatilization results in an increase in the total N content of the litter by as much as 12%. These findings were supported by a large scale study conducted by Sims and Luka-McCafferty (2002), who found that alum applications resulted in elevated total N concentrations compared to litter receiving no alum. In addition to increasing litter N:P ratios, this reduction in the volatilization of NH_3 from litter inside poultry production houses has been shown to decrease costs associated with ventilation and heating of the houses during winter months (Moore et al., 1998). Moore et al. (1998) showed that poultry production parameters such as mortality and feed conversion were improved by the use of alum at the recommended rate of 0.09 kg alum bird^{-1} because of reduced NH_3 concentrations in the production facility. Worley et al. (2000) later showed that these benefits could also be attained by using a rate of 0.05 kg alum bird^{-1} with increase economic benefit.

Treatment of poultry litter with alum results in other environmental benefits as well. Specifically, Moore et al. (1998) found that the treatment of poultry litter with alum significantly reduced runoff concentrations of arsenic, copper, iron, and zinc from fescue pasture compared to NPL applications. These decreased metal concentrations were associated with decreased soluble organic carbon concentrations found in runoff collected from treatments receiving ATPL. Similarly, Nichols et al. (1997) found that applications of ATPL resulted in 42% lower concentrations of 17β-estradiol, an estrogen hormone, compared to NPL when applied on an equal dry weight basis.

Need for Additional Evaluation of ATPL

Despite the volume of research conducted evaluating the consequences of treating poultry litter with alum, the need for continued research remains. Little is known as to how the use of ATPL will affect crop productivity when it is applied at rates based on currently required litter management strategies in Virginia. Specifically little is known about the impact of appling ATPL to soils containing soil test P at levels below optimum for crop production. In addition the impact of using ATPL as a nutrient source has not been evaluated in conventionally tilled systems. Questions remain as to the effectiveness of ATPL in reducing P availability to surface runoff in these conventionally tilled systems. The long-term impact of ATPL applications on the distribution of P in soils has not been evaluated. Because of the increased Al, S and N concentrations in ATPL, its application has the potential to result in lower soil pH values compared to applications of NPL. In fact, concerns as to its impact on exchangeable Al concentrations in soils receiving ATPL have been raised.

Therefore, the objectives of the body of work presented here were to:

1.   Evaluate the impact of using ATPL as a nutrient source on the production of field corn (*Zea mays* L.) and tall fescue;

2.   Evaluate the long-term impact of ATPL applications on the P status of soils as determined by routine soil test P analyses;

3.   Evaluate the impact of ATPL on soil pH and exchangeable Al; and

4.   Evaluate changes in the distribution of soil P after long-term applications of ATPL.

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Chapter 2: Environmental and Production Consequences of using Alum-amended Poultry Litter as a Nutrient Source for Corn

Abstract

Field trials were established to compare alum-treated poultry litter (ATPL), normal poultry litter (NPL) and triple superphosphate (TSP) as fertilizer sources for corn (*Zea mays* L.) when applied at rates based on current litter management strategies in Virginia. Trials were established in the Coastal Plain and Piedmont physiographic regions near Painter and Orange, VA, respectively. Nitrogen based applications of ATPL or NPL applied at rates estimated to supply 173 kg of plant available N (PAN) ha^{-1} resulted in significantly lower grain yields than treatments receiving commercial fertilizer at the same rate in 2000 and 2001 at Painter. These decreases in grain yield at the N-based application rates were attributed to inadequate N availability, resulting from over estimates of PAN as demonstrated by tissue N concentrations. At Orange, no treatment effects on grain yield were observed. Applications of ATPL did not affect Al concentrations in corn ear-leaves at either location. Exchangeable soil Al concentrations were most elevated in treatments receiving only NH_4NO_3 as an N source. At N-based application rates, the ATPL resulted in lower Mehlich 1 extractable P (M1-P) and water extractable soil P (H_2O-P) concentrations compared to the application of NPL. A portion of this reduction could be attributed to lower rates of P applied in the N-based ATPL treatments. Runoff collected from treatments that received ATPL two days prior to conducting rainfall simulations contained 61 to 71 % less dissolved reactive P (DRP) than treatments receiving NPL. These results show that ATPL may be used as a nutrient source for corn production without significant management alterations. ATPL can also reduce the environmental impact of litter applications, primarily through minimizing the P status of soils receiving long-term applications of litter and reductions in runoff DRP losses shortly after application.

Abbreviations:
ATPL: Poultry litter treated with alum.
3CR: Phosphorus application rate of 73 kg P ha^{-1}, applied once prior to planting in 2000.
CR: Phosphorus application rate of 24 kg P ha^{-1}.
DRP: Dissolved Reactive P.
H_2O-P: Water extractable soil P.
M1-P: Mehlich 1 extractable soil P.
NBAL: Phosphorus application rate based on the carrier P in ATPL applied to supply 173 kg PAN ha^{-1}.
NBNL: Phosphorus application rate based on the carrier P in NPL applied to supply 173 kg PAN ha^{-1}.
NPL: Normal poultry litter without alum additions.
PAN: Plant available N.
TSP: Triple superphosphate fertilizer.

Introduction

Historically, poultry (*Gallus gallus domesticus*) litter has been utilized as a fertilizer source for agricultural fields. Because N is often the most limiting nutrient for crop production, litter has typically been applied at rates to supply adequate amounts of N for crop production. The N:P ratio found in poultry litter ranges from 0.6 to 1.0 (Evanylo and Mullins, 2000), yet the ratio of N removed to P removed by crops grown in Virginia ranges from 2.0 in cotton (*Gossypium hirsutum* L.) to 9.0 in peanuts (*Arachis hypogaea* L.) (Donohue, 2000). Therefore, long-term applications of poultry litter result in elevated soil test P levels (Kingery et al., 1994; Sharpley et al., 1993). In fact, many soils found near areas of high poultry production in Virginia, which have historically received litter applications, currently have high to very high M1-P levels (>28 mg P kg^{-1} soil) (Brosius et al., 2000).

Increases in soil test P due to poultry litter applications can correspond to an increase in soluble P concentrations in surface water runoff (Sharpley, 1995). This increase can lead to P loading of surface water bodies. Phosphorus is the limiting nutrient in most aquatic systems; therefore, the addition of non-point source P pollution from agricultural lands can be a contributor to eutrophication of sensitive water bodies (Pote et al., 1996). Thus, major efforts are being made by policy makers to curb non-point source P pollution in surface water bodies. For example, Virginia's Poultry Waste Management Act of 1999 requires poultry producers to have P-based nutrient management plans, which limit poultry litter application rates to crop requirements of P, based on soil test recommendations or crop removal of P, whichever is greater. The Delaware Nutrient management Act of 1999 mandates that P applications to soils containing high P concentrations be no greater than the estimated 3-year crop removal (Sims, 1999). Maryland's Water Quality Improvement Act of 1998 also requires producers to adopt P-based nutrient management plans (Simpson, 1998). Because many soils located relatively near poultry production operations already contain high to very high levels of soil test P, litter applications will most often be limited to rates equal to crop P removal. This limitation results in a dramatic increase in the land base needed for the utilization of poultry litter produced as well as increased costs associated with transporting litter away from poultry production facilities. It also increases the needs for supplemental commercial N fertilizer to fulfill the N requirements for crops grown on fields treated with poultry litter.

In addition to decreasing application rates to reduce soil P loading, other management options are being evaluated to reduce water quality impacts of using poultry litter as a nutrient source. One potential management practice for reducing the solubility of P in poultry litter is the use of chemical amendments. Many Ca, Al, and Fe containing compounds such as alum ($Al_2(SO_4)_3 \bullet 16H_2O$) and ferrous sulfate ($FeSO_4 \cdot 7H_2O$) (Shreve et al., 1996), sodium aluminate ($Na_2Al_2O_4$), quicklime (CaO), slaked lime [$Ca(OH)_2$], calcitic limestone ($CaCO_3$), dolomitic limestone [$CaMg(CO_3)$], gypsum($CaSO_4 \cdot 2H_2O$), ferrous chloride($FeCl_2 \cdot 4H_2O$), ferric chloride($FeCl_3$), and ferric sulfate[$Fe_2(SO_4)_3 \cdot 2H_2O$] (Moore and Miller, 1994) have been evaluated for their effectiveness in reducing soluble P in poultry litter. Of these amendments, alum has been shown to be an economically viable option for reducing the solubility of P in poultry litter (Moore et al., 1999) and is beginning to be used by producers. In a farm-scale study utilizing 194 poultry houses,

half of which received alum additions, Sims and Luka-McCafferty (2002) found alum-treated poultry litter (ATPL) to contain 73% lower H_2O-soluble P in litter compared to normal poultry litter (NPL).   In a pen trial, Miles et al. (2003) found that the use of alum resulted in as much as a 60% reduction in H_2O-soluble P found in litter depending on dietary formulation. These reductions in H_2O-soluble P can be attributed to the adsorption of P to amorphous aluminum hydroxides that form in poultry litter after the addition of alum (Peak et al., 2002).

In addition to reduced P solubility, alum, when applied to the floor of production houses prior to the addition of each flock of birds, reduces NH_3 volatilization from poultry litter (Moore et al., 1995). This decrease in NH_3 volatilization results in an increase in the N content of the litter. Therefore, the value of the litter as a N source and its N:P ratio may be increased.

The use of ATPL in field trials has yielded results that demonstrate its effectiveness in minimizing P availability. Shreve et al. (1995) found that when applied to tall fescue (*Festuca arundinacea* Schreb.), the reduced concentration of H_2O-soluble P in ATPL resulted in an 87 % reduction in the concentration of dissolved reactive P (DRP) in runoff compared to plots receiving the same amount of NPL. Moore et al. (1999) demonstrated that three annual applications of ATPL to tall fescue, resulted in lower H_2O-P and Mehlich 3 extractable P compared to NPL, when both were applied at rates of 2.24, 4.49, 6.73, and 8.98 Mg litter ha^{-1}. At the highest rate of 8.98 Mg litter ha^{-1}, H_2O-P increased to approximately 40 mg P kg^{-1} in treatments receiving NPL compared to approximately 10 mg P kg^{-1} in the control treatment receiving no P fertilizer. In comparison, H_2O-P in the treatment receiving the corresponding ATPL rate was approximately 15 mg P kg^{-1}, which was not significantly different from that found in the control treatment receiving no P fertilizer. The addition of ATPL at the 8.98 Mg ha^{-1} rate significantly increased Mehlich 3 extractable P compared to the control treatment receiving no P fertilizer, but was still nearly one half the concentration found in the treatment receiving the same rate of NPL.

Additional field research has found that the treatment of poultry litter with alum has additional beneficial effects on surface runoff water quality. Specifically Moore et al. (1998) found that the treatment of poultry litter with alum significantly reduced runoff concentrations of arsenic, copper, iron, and zinc from fescue pastures compared to NPL applications. These decreased metal concentrations were associated with decreased soluble organic carbon concentrations found in runoff collected from treatments receiving ATPL.   Similarly, Nichols et al. (1997) found that applications of ATPL resulted in 42% lower concentrations of 17β-estradiol, an estrogen hormone, compared to NPL when applied on an equal dry weight basis.

Currently, limited field research data are available for the evaluation of ATPL as a nutrient source for crop production. As mentioned, Shreve et al. (1995) applied equivalent amounts of ATPL and NPL to tall fescue and found that applications of ATPL resulted in a 28 % increase in total forage yield compared to NPL. Because litter sources were applied on an equal weight basis these increased yields were attributed to the higher N concentrations in ATPL resulting from decreased ammonia volatilization as reported by Moore et al. (1995). In the study conducted by Moore et al. (1995), NH_4-N concentrations found in poultry litter 42 days after the addition of 130 g of alum kg^{-1}

were increased from 3.3 g N kg^{-1} in the control to as much as 11.2 g N kg^{-1} in the ATPL. Assuming the NH$_4$-N concentrations in litter used by Shreve et al. (1995) were similar to those reported by Moore et al. (1995), the NPL and ATPL applied at the rates used by Shreve et al. (1995) would have supplied approximately 37 and 125 kg NH$_4$-N ha^{-1}, respectively. This adequately explains the increased forage yields resulting from the use of ATPL.

Currently, no data are available in the literature where ATPL has been evaluated as a nutrient source for field crops such as corn (*Zea mays*). Specifically, no data are available evaluating ATPL and NPL applied at equivalent plant available N and/or equal P rates. The possibility of increased exchangeable Al in soils treated with ATPL has received minor attention (Moore et al., 1999); however, the effect of ATPL applications on the P status of cultivated soils has not yet been evaluated. Because of decreased vegetative cover in a cultivated system compared to pasture systems, greater concentrations of total P loss may be expected in runoff from cultivated systems due to a higher potential for losses of litter particles and sediment (Sharpley et al., 1992). Of this P lost to runoff in cultivated systems, a smaller percentage is expected to be in soluble forms compared to P lost from pasture systems (Edwards and Daniel, 1993). These effects could impact the value of alum treatment as an option in reducing P losses. Therefore, it is important to evaluate alum treatment of poultry litter as a management practice to reduce P runoff from cultivated cropping systems.

The objective of this study was to evaluate production and environmental impacts of using ATPL as a nutrient source for corn production in accordance with current litter management strategies. The response of corn yield and elemental plant tissue concentrations to application of ATPL was evaluated. Also, the environmental impact of using ATPL was assessed through evaluation of changes in soil P status, soil exchangeable Al content, and soil pH resulting from applications of ATPL. In addition simulated rainfall experiments were conducted to evaluate the effects of using ATPL on P runoff concentrations.

Materials and Methods

Small plot field experiments were conducted at Virginia Tech's Northern Piedmont and Eastern Shore Agricultural Research & Extension Centers in Orange and Painter, VA, respectively from 2000 through 2003. Field corn (Pioneer 31G20) was planted at a rate of 55,600 kernels ha^{-1} in 0.91-m rows. Plots were 6 rows wide and 6.1-m long. The experimental area at Painter was on a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludult). The experimental area at Orange was on a Davidson loam (fine, kaolinitic, thermic Rhodic Kandiudult).

Poultry Litter

Poultry litter used in the study was collected from two poultry houses included in the study presented by Sims and Luka-McCafferty (2002). One of the houses received alum at an approximate rate of 0.09 kg bird^{-1} prior to the introduction of each flock. The second house received no alum additions. Litter was collected at the end of a grow-out and transported to the research stations and stored in barrels until application. The

average elemental compositions of the litters are presented in Table 1. The analyses were conducted by the University of Maryland Soil Testing Laboratory for the 2000 and 2001 growing seasons and by the Agricultural Service Laboratory, Clemson University for the 2002 growing season.

Field Studies

Treatments consisted of triple superphosphate (TSP), ATPL and NPL, applied at four different phosphorus rates (Table 2). In addition to a no-phosphorus control treatment, phosphorus rates were based on: (1) applying NPL at rates to meet the nitrogen (N) needs of the crop (NBNL); (2) applying ATPL at rates to meet the N needs of the crop (NBAL); (3) annual estimated crop removal of P (CR); and (4) estimated three year crop removal of P (3CR). The 3CR treatments were applied prior to planting only in the 2000 crop-year and supplemental N was applied in 2001 and 2002 to these treatments. This resulted in a total of 11 treatments, which were arranged in a randomized complete block design with four replications per treatment. This treatment structure was selected to evaluate ATPL under currently recommended/required nutrient management strategies employed in Virginia. At Painter, the control treatment did not receive any N fertilizer in 2002, which was done to evaluate the N response in the other treatments.

All plots were supplied with sufficient N for estimated corn grain yields of 8.8 Mg ha^{-1} (equivalent to 173 kg PAN ha^{-1}, assuming a requirement of 19.7 kg N Mg^{-1} of corn grain yield) (Evanylo and Alley, 1998) (Table 2). The availability of N in the NPL and ATPL was estimated using guidelines developed by the Virginia Department of Conservation and Recreation (Virginia Department of Conservation and Recreation, 1995).   These guidelines assume that 90 % of the NH_4-N and 60 % of the organic-N is available as plant available N (PAN) for crop uptake in the year of application when litter is incorporated immediately after application. Phosphorus sources and supplemental N fertilizer were pre-plant broadcast applied and incorporated immediately prior to planting. Because soil test K levels were below optimum, supplemental K fertilizer was applied at Orange to all treatments to supply 112, 67, and 67 kg K_2O ha^{-1} in 2000, 2001 and 2002, respectively. No supplemental potassium fertilizer was applied at Painter.

Corn grain yields were determined at maturity by harvesting the full length of the two center rows from each plot using a plot combine at Painter and by hand harvesting at Orange. Corn grain was weighed and subsampled by plot for moisture determination and elemental analysis. Corn grain yields are reported at a moisture content of 0.155 g kg^{-1}. Composite corn ear leaf samples were collected at mid-silk from rows two and five in each plot. Ear leaf samples were not collected during the 2000 growing season at Orange. Plant tissue samples were dried at 65 ºC, ground and digested using a nitric acid and hydrogen peroxide digestion procedure (Jones and Case, 1990). The digests were analyzed for P and Al with atomic emissions spectroscopy using a SpectroFlame Modula Tabletop ICP-AES, Spectro Instruments, Fitchburg, MA. Tissue N concentrations were determined on ground samples with combustion and gas chromatography using an NC 2100 Analyzer, CE Instruments, Lakewood, NJ.

Composite soil samples were collected to a depth of 15 cm from the study areas prior to initiation and from each plot at 6 and 12 months after each treatment application.

Soil samples were air dried and ground to pass a 2-mm sieve. Samples collected prior to the initiation of the study were analyzed for pH (1:1 soil to water ratio) (Thomas, 1996), and extracted using the Mehlich I dilute-double acid procedure (Kuo, 1996). Mehlich I extracts from these initial samples were analyzed for Ca, Mg, K, and P. The pH values found in initial soil samples collected at Painter and Orange were 6.0 and 6.2, respectively. The concentrations of Ca, Mg, K, and P were 793, 102, 140, and 71 mg kg^{-1}, respectively, at Painter; and 725, 143, 98, and 9 mg kg^{-1}, respectively, at Orange. Samples collected from each plot were analyzed for Mehlich I soil test P (M1-P) (Kuo, 1996), water extractable P (H$_2$O-P) (1:10 soil to water ratio) (Kuo, 1996), exchangeable Al (1:5 soil to 1 N KCl ratio) (Bertsch and Bloom, 1996), and pH (1:1 soil to water ratio) (Thomas, 1996).

Rainfall Simulations

Two sets of rainfall simulations were conducted in the corn experiment located at Orange. The first set of rainfall simulations was conducted in May 2003, approximately one year after treatment application and incorporation. The second set of rainfall simulations was conducted in August 2003, two days after the application of treatments without incorporation. These treatments were applied only to evaluate runoff P concentrations shortly after application. Simulations were carried out in accordance with the protocol established as part of the national P research project (SERA-IEG 17, 2001). Duplicate sub-plots were established within treatments that had received the following treatments: NPL, ATPL, and TSP applied at the N-based and P crop removal rates as well as the no P control. For each set of simulations, two rainfall events were conducted on each sub-plot at one-day intervals. Rainfall was applied at a rate of 70 mm hr^{-1} and continued for 30 min after initiation of runoff. The weight of runoff was determined every 5 min during this 30 min period. Subsamples were taken for chemical analysis at each 5 min interval. Also, the total runoff volume collected 30 min after runoff initiation was mixed and sub-sampled. A portion of the subsamples were filtered through a 0.45-μm filter and acidified with HCl. Concentrations of DRP (Molybdate blue, (Murphy and Riley, 1962)) in filtered samples were determined. Unfiltered samples were analyzed for total P after Kjeldahl digestion with mercuric oxide and potassium sulfate catalyst (Lachat, 1995). Total C in runoff was determined on residue from 60 mL of runoff dried at 110 °C with combustion and gas chromatography using an NC 2100 Analyzer, CE Instruments, Lakewood, NJ. Sediment was determined by the weight of residue remaining after 20 mL of runoff was dried at 110 ºC.

Analysis of variance, using the SAS PROC GLM procedure (SAS Institute, 2001), was used to determine significant treatment effects on measured response variables. When treatment effects were found to be significant, Fisher's protected LSD was used to separate means. Regression analyses were conducted using the SAS PROC REG procedure.

Results and Discussion

Crop Response

Corn grain yields at Painter were significantly affected by treatment in 2000 and 2001 (Table 3), but were suppressed due to less favorable growing conditions (Table 4) and therefore not affected by treatments in 2002. In 2000 and 2001 at Painter, yields from treatments receiving applications of NPL and ATPL applied on an N-basis (NBNL and NBAL) were significantly lower than yields from treatments receiving equivalent rates of inorganic fertilizer (Table 3). This suggests that the method used to estimate N availability overestimated PAN in the two litter sources at this location.

Concentrations of N in ear-leaves collected at mid-silk from Painter suggest that these yield reductions were due to decreased N availability prior to flowering. The decreased N status of corn receiving litter at the N-based rate is also apparent when comparing corn grain N concentrations, specifically in 2001 (Table 3). Jones et al. (1990) stated that concentrations of N in ear-leaves collected at mid-silk are sufficient in the range of 21 to 40 g N kg^{-1}. Nitrogen concentrations in ear-leaves collected from treatments receiving NPL or ATPL at N-based application rates were consistently below this range at Painter (Table 3). Within the N-based treatments, ear-leaf N concentrations were well correlated with grain yield during the first 2-years of the study at Painter (Fig. 1). The correlation between ear-leaf N and grain yield was not significant in 2002 due to suppressed yields. In 2000 and 2001, the yields from treatments receiving NH_3NO_4 as the primary PAN source (Table 2) were as much as 4.2 Mg ha^{-1} higher than the estimated yield of 8.8 Mg ha^{-1}; whereas, yields from those treatments receiving all or most of the PAN as poultry litter were equivalent to or below 8.8 Mg ha^{-1} at Painter due to an overestimation of PAN at the Painter location for both sources of poultry litter. The data demonstrate the importance of using tools such as the pre-side dress nitrate test (Evanylo and Alley, 1998) to evaluate mid-season soil N status of corn fertilized with poultry litter. Although not significant, the ear-leaf N concentrations in the treatment receiving ATPL at the N-based rate were consistently lower than those found in the treatment receiving NPL at the N-based rate during each year of the study (Table 3), further suggesting decreased N availability and an overestimation of PAN in treatments receiving ATPL compared to NPL. These consistent yet non-significant results could imply a minor difference in the availability of N found in the two litter sources, which would be inconsistent with previous research. Gilmour et al. (2004) recently conducted laboratory incubations to evaluate the effects of alum treatment on the decomposition and N mineralization rates of poultry litter and found no significant differences in the N mineralization rates of ATPL and NPL. Unlike conditions for this laboratory study, field conditions at Painter were likely not optimum for N mineralization as can be seen from the reduced yields produced by both litter sources applied on a N-basis compared to inorganic fertilizer. These sub-optimum conditions could have magnified any differences among mineralization rates of the two litters.

In addition to the N-based application rates, applications of NPL and ATPL at the 3CR P rate at the Painter site in 2000 resulted in significantly lower yields than an equivalent application of inorganic fertilizer (Table 3). Also, for the 3CR P rate in 2000 the yield from the NPL source was significantly greater than yields from ATPL. At the

3CR P rate the ATPL treatment received all but 10 kg PAN ha^{-1} as ATPL whereas the NPL treatment received an additional 66 kg PAN ha^{-1} as NH_4NO_3 (Table 2). This supplemental N applied as NH_4NO_3 contributed to the increased yield response to the NPL applied at the 3CR P rate compared to the equivalent ATPL treatment. These differences at the 3CR P rate did not persist in 2001 and 2002 because these treatments received NH_4NO_3 as the sole N source and no additional poultry litter. Also, ear-leaves collected during the 2000 crop year from treatments receiving NPL or ATPL at the 3CR P rate had 19 and 20 % lower N concentrations, respectively, than ear-leaves collected from treatments receiving equivalent rates of inorganic fertilizer (Table 3). This response in ear-leaf N concentration was similar to that found in grain yield. Again both the ear-leaf N and grain yield data from the 3CR P rate in 2000 suggests that PAN was overestimated at the Painter location as was found in the N-based rates.

No significant differences in grain yield or tissue N were found at Painter among sources applied at the CR rate. The average yields for the CR P rate at Painter were 12.4, 10.9, and 2.4 Mg ha^{-1} in 2000, 2001, and 2002, respectively. The NPL and ATPL sources applied at the CR rate supplied 21 and 31 % of the PAN applied to these plots, with the remaining PAN applied as NH_4NO_3. This combination of litter and supplemental inorganic N was adequate to produce yields similar to those treatments receiving only inorganic fertilizer.

The concentrations of ear-leaf P follow a similar trend as that found in ear-leaf N concentrations at Painter (Table 3). At the N-based P application rates, ear-leaf P concentrations were consistently lower in treatments receiving either ATPL or NPL compared to treatments receiving TSP. Also, in ear-leaves collected in 2000 the P concentrations were reduced in treatments receiving either ATPL or NPL at the 3CR P rate compared to those found in ear-leaves collected from the treatment receiving the equivalent rate of P as TSP. The lack of significant differences between the control treatment which received no P and the TSP treatments shows that the site was unresponsive to additional P. Therefore the suppressed ear-leaf P concentrations found in the litter treatments are more likely due to interactions between N availability and P uptake.

Because no response in tissue N concentration to the N availability among sources was observed at the CR P rate, this P rate can be used to investigate differences in P availability among the P sources. At Painter no significant differences in the ear-leaf P concentrations were found among treatments receiving the three P sources at the CR P rate (data not shown), nor were these ear-leaf P concentrations different from those found in the 0-P check treatment. This demonstrates a lack of crop response to CR rates of P additions at Painter.

Results from Orange are similar to those found by Gilmour et al. (2004) in that there were no apparent yield responses due to difference in N availability among sources. No significant (p<0.05) treatment by year interactions were observed in grain yield and upon combining yield data over years no significant treatment effects were observed (Table 5). Prior to the initiation of this study at Orange, the M1-P level was 7 mg P kg^{-1}. At this level of M1-P the Virginia Tech Soil Testing Laboratory recommends a fertilizer application of 39 kg P ha^{-1} (Donohue, and Heckendorn, 1994), yet no grain yield

response to P fertilizer applications of as high as 116 kg P ha^{-1} (P application resulting from the NBNL rate) were observed at Orange.

At Orange there were no significant year by treatment interactions (p<0.05) for ear-leaf P or N content, or for grain N or P content; therefore, ear-leaf and grain N and P concentration data were combined over years (Table 5). No significant differences, due to treatment, in ear-leaf N or P concentrations were found at Orange. The ear-leaf N and P concentrations found at Orange were well within the sufficiency range presented by Jones et al. (1990) and demonstrated a lack of mid-season response to pre-plant P and N fertilizer application. There were also no significant differences in grain N concentrations among treatments. However, when the concentration of grain P is averaged for each treatment across years there were significant treatment effects. Specifically, the rate of application significantly affected the concentration of P in the grain with no significant differences among sources at any rate. Averaged over the 3-year study at Orange, the N-based treatment applications resulted in a grain P concentration of 2.8 g P kg^{-1}, which was significantly greater [LSD$_{(0.05)}$ = 0.3] than concentrations resulting from the 0-P check, and the CR P application rate, and 3CR P application rate, which resulted in average concentrations of 2.5, 2.5, and 2.6 g P kg^{-1}, respectively (Table 5). The lack of differences in corn grain P concentrations among the three sources confirms previous research evaluating crop P uptake from ATPL treated soils which found only minor differences in tissue P concentrations between treatments fertilized with ATPL and NPL. Shreve et al. (1995) evaluated nutritional composition of fescue receiving non-amended litter and litter treated with alum (1:5 amendment:litter ratio) at a rate of 11.2 Mg ha^{-1}. They found that P concentrations in harvested fescue forage receiving ATPL were lower at 6.5 g P kg^{-1}, but not significantly lower than fescue receiving NPL, which contained 7.3 g P kg^{-1}. This decline in tissue P was attributed to a dilution of P due to increased plant growth from the ATPL treatment.

Aluminum Availability

The addition of ATPL did not result in significant treatment by year interactions nor were there significant treatment effects on corn grain or ear leaf Al concentrations (p<0.05). The average corn grain Al concentrations being similar at both locations were 25.8 and 28.3 mg Al kg^{-1} at Painter and Orange, respectively. In contrast, the average ear leaf Al concentration at Painter was nearly 3-times greater at 88 mg Al kg^{-1} than that found at Orange, which averaged 33 mg Al kg^{-1}. Despite this difference, ear leaf Al concentrations at both locations were well within the expected normal range of 10 to 200 mg Al kg^{-1} suggested by Jones et al. (1990). The lack of significant differences in tissue Al concentrations among sources is inconsistent with the findings of Shreve et al. (1995) who reported significantly higher Al concentrations in tall fescue treated with ATPL (91 g Al kg^{-1}) compared to that found in tall fescue forage treated with NPL (48 g Al kg^{-1}).

Although no differences in tissue Al concentrations were found, there were significant treatment differences in soil pH and exchangeable soil Al concentration. At Painter the N-based applications of ATPL and NPL resulted in significantly elevated pH levels and subsequently lower exchangeable Al concentrations compared to treatments receiving equivalent applications of commercial fertilizer (Table 6). These results are consistent with findings of Kingery et al. (1994) who found that long term applications of

poultry litter to pastures resulted in increased soil pH.   Moore et al. (1999) discussed findings from field studies conducted in Arkansas, in which they found that the pH of soils receiving either NPL or ATPL was elevated compared to that of soils receiving ammonium nitrate (NH_4NO_3). At Orange the N-based applications of NPL again resulted in significantly higher soil pH and decreased exchangeable Al compared to the treatment receiving equivalent rates of commercial fertilizer. Application of ATPL at the N-based rate did not elevate pH at Orange compared to equivalent applications of commercial fertilizer. This lack of increased soil pH could be a result of lower rates of litter application associated with the ATPL compared to NPL (Table 2). Also, the acidity of the alum added to the litter would have been neutralized by carbonates and other bases present in the litter. Because of this acid neutralization the carbonate equivalent of the ATPL is likely lower than that of NPL. These two factors, along with the increased buffer capacity of the Davidson soil compared to the Bojac soil did not allow the ATPL to increase soil pH as was found at Painter. At Orange, the pH and Al concentrations in treatments receiving ATPL at the 3CR rate more closely resembled those treatments receiving TSP at the equivalent rate.

Given the variations in soil pH and exchangeable Al associated with treatment, it is important to evaluate the effect of applying ATPL on the relationship between pH and the Al concentration in these soils. The relationships between pH and exchangeable Al concentration across P sources at Painter and Orange are illustrated in Fig. 2. Alum treated poultry litter had no effect on the slope or intercept of the line representing this relationship at either location.   These findings show that although ATPL may not be as effective in maintaining soil pH compared to NPL, it did not affect exchangeable Al concentrations at a given soil pH.

Soil P status

Significant changes in M1-P were observed at both locations in soil samples collected in the fall of 2002 (Table 7). At Painter, M1-P in treatments receiving annual applications of ATPL at the NBAL rate was 37 % lower than those receiving NPL at the NBNL rate while at Orange, this reduction was 32 %. Some of these differences in M1-P concentrations may be a result of differences in the net P application rates resulting from N-based applications of the two litter sources (Table 7). However, these data can be used to show that each kg of net P applied per ha in ATPL results in a lower increase in the M1-P concentration compared to the two other sources.   For example, when the difference in M1-P concentrations found in the control and the treatment receiving ATPL at the NBAL rate is divided by the difference in the net P applied to these two treatments it is found that the M1-P concentration increases by 0.09 mg P kg^{-1} for each kg of net P applied ha^{-1} at the Painter location. However, when this ratio is calculated for the NPL or TSP applied at the N-based rates at Painter, the M1-P concentration increases by approximately 0.2 mg P kg^{-1} for each kg of net P applied ha^{-1}. These results suggest that using ATPL can result in lower M1-P levels even when net P additions are equal to or greater than additions of TSP or NPL. The total P applied to the CR and 3CR P treatments were nearly equal to the total P removed from these treatments at Painter (Table 7). At Orange the net P addition for these treatments ranged from 9 to 19 kg P ha^{-1}. As a result, minimal changes in M1-P concentrations were observed. In fact, the

application of TSP at the CR P rate at Painter was the only CR treatment at either location to result in M1-P concentrations significantly greater than the control (Table 7).

Soil concentrations of H_2O-P in the fall of 2002 followed trends similar to changes in M1-P (Table 7). Neither the CR nor the 3CR P rates, irrespective of source, resulted in significant increases in H_2O-P concentrations compared to the 0-P check treatment. Applications of ATPL at the NBAL rate resulted in 54% and 56% lower H_2O-P concentrations than the application of NPL at the NBNL rates at Painter and Orange, respectively. Moore et al. (1999) showed only a minor, non-significant difference in the H_2O-P content of soils receiving 169 kg P ha^{-1} as ATPL when compared to the 0-P check, yet found a 4-fold increase in H_2O-P in soil receiving 201 kg P ha^{-1} as NPL when applied for three years to tall fescue. Their findings are similar to those from Orange and Painter but lack TSP treatments for comparison. In contrast to the trends found in M1-P, there was no difference in H_2O-P concentrations between treatments receiving TSP or ATPL at the NBAL rate (Table 7). These data suggest that although the ATPL additions result in less labile solid phase P as compared to TSP, the addition of Al to the soil in the ATPL is not sufficient to decrease the solution phase P solubility in these soils to a level significantly below that found in treatments receiving equivalent rates of TSP. This lack of significant difference in the H_2O-P concentrations between treatments receiving ATPL and TSP, specifically at the NBAL rate, may be explained by the lower pH and subsequently higher exchangeable Al concentrations in the TSP treatment (Table 6). This effect of pH on the H_2O-P concentrations was most prominent at the Painter location where no significant difference was found between ATPL and TSP applied on a N-basis although both treatments resulted in H_2O-P concentrations that were higher than the no-P control. The same pH effect could also explain the decreased solubility of P in treatments receiving TSP at the NBNL rate compared to treatments receiving NPL at the NBNL rate.

Phosphorus Loss in Simulated Runoff

Due to the lack of significant differences and variability in the volume of runoff from the small plots used in this study, runoff data are presented as concentrations. Although DRP concentrations were low in the first and second rainfall events, which were conducted in May 2003 prior to a fourth P application, significant differences were found among treatments (Table 8). Treatments that had received 3 years of the N-based applications of all three P sources resulted in significantly higher runoff DRP during the first events as compared to the control treatment. During the second event only, the N-based treatments receiving NPL and TSP resulted in DRP concentrations significantly greater than the control. Alum-treated poultry litter applied at the NBAL rate resulted in the lowest DRP concentrations in runoff during the first and second events compared to the other two sources of P applied on an N-basis (Table 8). This is a result of the lower M1-P concentrations found in treatments receiving ATPL applied on a N-basis as compared to those receiving TSP or NPL (Table 7). The DRP concentrations found in runoff from both events were well related with M1-P and there were no significant differences in the slope or intercept of the relationships found during the two rainfall events (Fig. 3). There were no significant differences in runoff total P concentrations among treatments during the first and second events (Table 8).

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Dissolved reactive P and total P concentrations in runoff from treatments that received P applications two days prior to the set rainfall events are shown as the third and fourth runoff events in Table 8. The concentrations of DRP and total P in runoff from each of these rainfall events were significantly affected by treatment (Table 8). The ATPL applied at the NBAL rate resulted in 61% less DRP in runoff during the first event following application compared to the NPL applied at the NBNL rate. Lower DRP can be attributed to the decreased P solubility in ATPL. Although soluble P was not measured on litter used in this study, previous work has shown that the amendment of poultry litter with alum reduces H_2O soluble P in litter on average by 73% when treated to produce litter with Al to P ratios of 0.57 (Sims and Luka-McCafferty, 2002). The litters used in our study were collected from poultry production facilities included in the study presented by Sims and Lua-McCafferty (2002) and the ATPL had an Al to P ratio of 0.51, therefore it likely has very similar soluble P concentrations. Evidence of the effect of decreased P solubility in the ATPL is found when DRP concentrations in runoff from plots receiving ATPL and TSP applied at the NBAL rate are compared. At this rate, DRP concentrations were 48% lower in runoff during the third event from the ATPL treatments compared to TSP treatments.   The effect of the lower P solubility in ATPL is also evident when comparing DRP concentrations found in runoff from treatments receiving CR rates of the three sources. At this rate, DRP from treatments receiving ATPL was 71 and 45 % lower as compared to runoff from NPL and TSP treatments, respectively (Table 8).

The runoff total P concentrations were generally higher for treatments receiving either NPL or ATPL compared to treatments receiving TSP during the third event (Table 8). This is especially evident at both N-based rates. In the N-based treatments, the DRP concentrations from treatments receiving TSP were nearly equal to the total P concentrations. In runoff from treatments receiving NPL at the NBNL rate, DRP accounted for 75 % of the total P, whereas DRP from treatments receiving ATPL at the NBAL rate accounted for only 32 % of the total P in runoff. Therefore, although litter applications resulted in greater total P losses, less of this P was in a soluble form as compared to TSP.   The lack of a significant difference in total P concentrations between NPL and ATPL is contradictory to previous research where applications of ATPL to fescue pastures resulted in 65 % lower total P in runoff than from fescue receiving non-amended litter applied on an equal weight basis (Moore et al., 2000). The row crop system evaluated in our study likely allowed for greater potential erosion and litter particle losses compared to the previous study conducted on fescue pasture. Therefore, total C in runoff was determined for use as an indicator of litter particle concentrations in runoff. Assuming the amount of total C in runoff gives an indication of the amount of litter particles lost in runoff, a substantially greater concentration of litter particles was present in the third runoff event from the treatment receiving ATPL at the NBAL rate compared to the treatment receiving NPL at the NBNL rate (Table 8). This is dissimilar to results from Moore et al. (1998) that showed decreased soluble organic C in runoff from fescue treated with ATPL as compared to treatments receiving NPL. The decrease in the concentrations of soluble organic C found by Moore et al. (1998) may be attributed to changes in the chemical character of litter treated with alum. However, the differences in the concentration of total C found among treatments in our study are likely due to physical differences between the two litter sources or differences in the hydrology of the

plots. Evidence of a hydrological effect is found when inconsistencies between the N-based treatments and the CR treatments are compared. Application of ATPL at the CR rate resulted in a 38 % lower total C concentration as compared to NPL, whereas at the N-based rate of ATPL resulted in a 32 % greater total C concentration. Despite these inconsistencies, the evaluation of total C concentrations in runoff helped to assess the resulting trends among total P concentrations. Specifically the lack of an expected significant difference in total P runoff concentrations among treatments receiving ATPL and NPL on an N-basis is due to elevated litter particle concentrations in runoff from the ATPL, NBAL treatment even though the amount of total P applied was 34 % less than that applied to the NPL, NBNL treatment. These results are similar to those found by Penn et al. (2004) who also found that total P losses are more a function of the amount of manure particles lost in runoff than of P application rates. The data highlight an important limitation in using small sub-plots to evaluate P loss in runoff, specifically, differences in hydrology of small runoff plots can have significant impacts on the results.

Conclusions

As a nutrient source for corn grain production, ATPL performed similarly to NPL. Data collected at Painter confirmed the importance of mid-season evaluations of the N status of corn when using poultry litter as the primary N source. The use of ATPL did not appear to affect the concentration of P in corn ear leaves or grain, even at Orange where soil test P levels (M1-P) were below the optimum range at the initiation of the study. Aluminum concentrations in corn ear leaves and grain were not increased in treatments receiving ATPL nor were the exchangeable Al concentrations in soils receiving ATPL increased. In fact, exchangeable Al concentrations were elevated only in treatments receiving NH_4NO_3 as the primary N source. At the N-based application rates, both M1-P and H_2O-P were lower in treatments receiving ATPL compared to NPL. Much of this reduction could be attributed to lower rates of total and net P applications in the ATPL treatments (Table 8). Through comparison to inorganic fertilizer treatments, additional reductions in M1-P concentrations could be attributed to the alum present in the litter. These reductions in M1-P concentrations resulted in decreased DRP losses in simulated runoff from soils 1-year after the third annual treatment applications. The most beneficial effect of litter treatment with alum was the reduction in DRP loss in runoff when rainfall occurred shortly after application. However, applications of ATPL did not result in consistently lower total P concentrations in runoff because of the apparent loss of litter particles when using small runoff plots in this cultivated row-cropping system. Inconsistencies in the amount of litter particles lost from the runoff plots were a result of shortcomings of the small simulated runoff plot method employed to determine runoff losses. The results point out that, when using small runoff plots, small-scale variations in hydrology can significantly impact simulation results. Therefore, although small-scale simulations are useful in comparing specific treatments, care should be taken when extrapolating the data to edge of field losses especially when evaluating systems shortly after litter application.

The experimental design employed in this study was useful in comparing environmental and production responses resulting from ATPL, NPL or TSP applied at "agronomic rates" as specified by local regulations.   These comparisons at agronomic

rates are important because much of the litter is now applied at these rates as mandated by government agencies. Previous research has focused on comparing ATPL to NPL when applied on an equal dry weight basis or at equal total P rates. The inclusion of rates determined by the estimated PAN content of litter allowed us to evaluate ATPL as a nutrient source and to evaluate the effectiveness of current regulations in meeting crop production and environmental goals.

Our study demonstrated inaccuracies in our current method of estimating PAN from both ATPL and NPL, which prompts interest in the reevaluation of these estimates, and highlighted the importance of in-season evaluations of the N status of the crop when using litter as the primary N source. However, the design of our experiment did not allow for direct comparisons of N availability between NPL and ATPL due to slightly different total N application rates for the two litters. Further research should focus on evaluating any differences in N mineralization rates between NPL and ATPL. Also, the addition of alum not only affects the availability of P in litter but may also reduce the liming value of the litter and, consequently, lower soil pH and P solubility in soil. Therefore, interactions among these factors should be considered in the design of future research studies.

In conclusion, the results of this study show that the use of ATPL can reduce runoff P and soil test P when using poultry litter as a nutrient source for corn production. These environmental benefits are achieved without the need for significant changes in production management strategies when utilizing ATPL.

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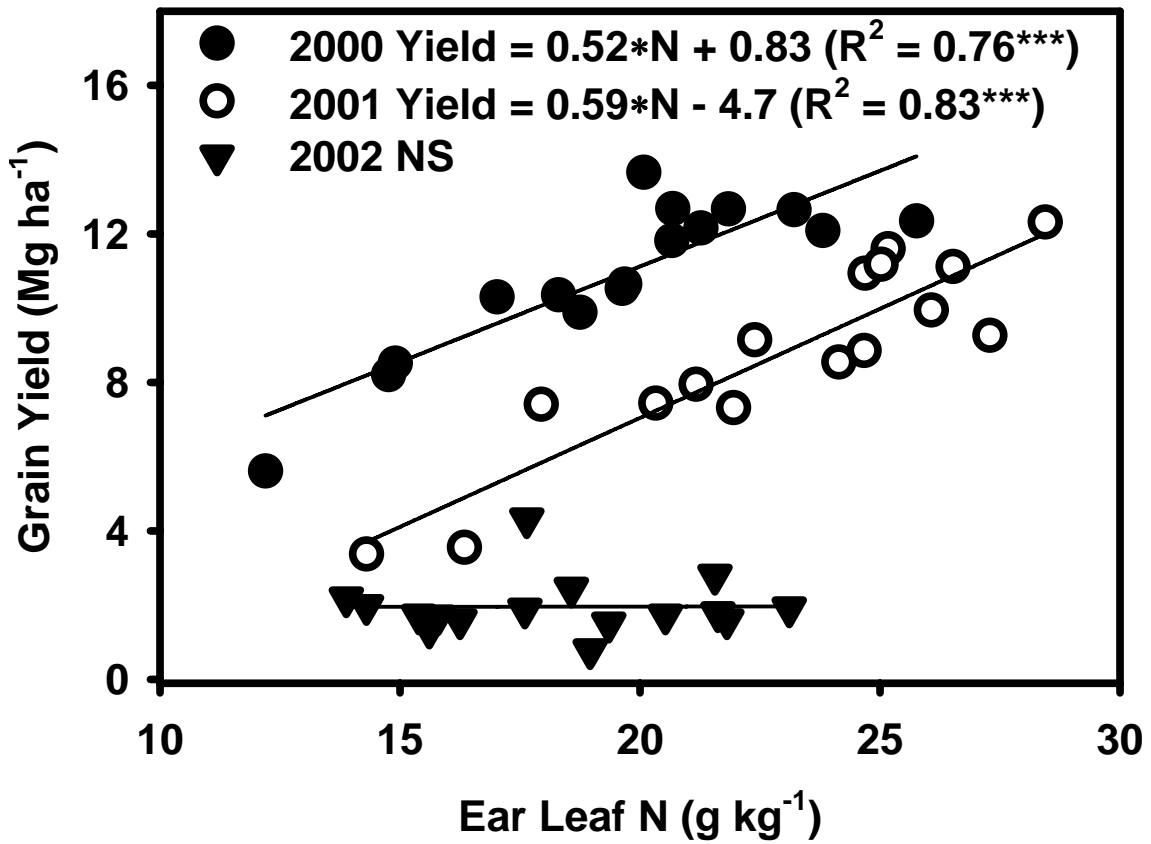
Fig. 2.1: The relationship between ear leaf N content and grain yield for the N-based treatments at Painter, VA (*** significant at the 0.001 probability level, NS= regression not significant).
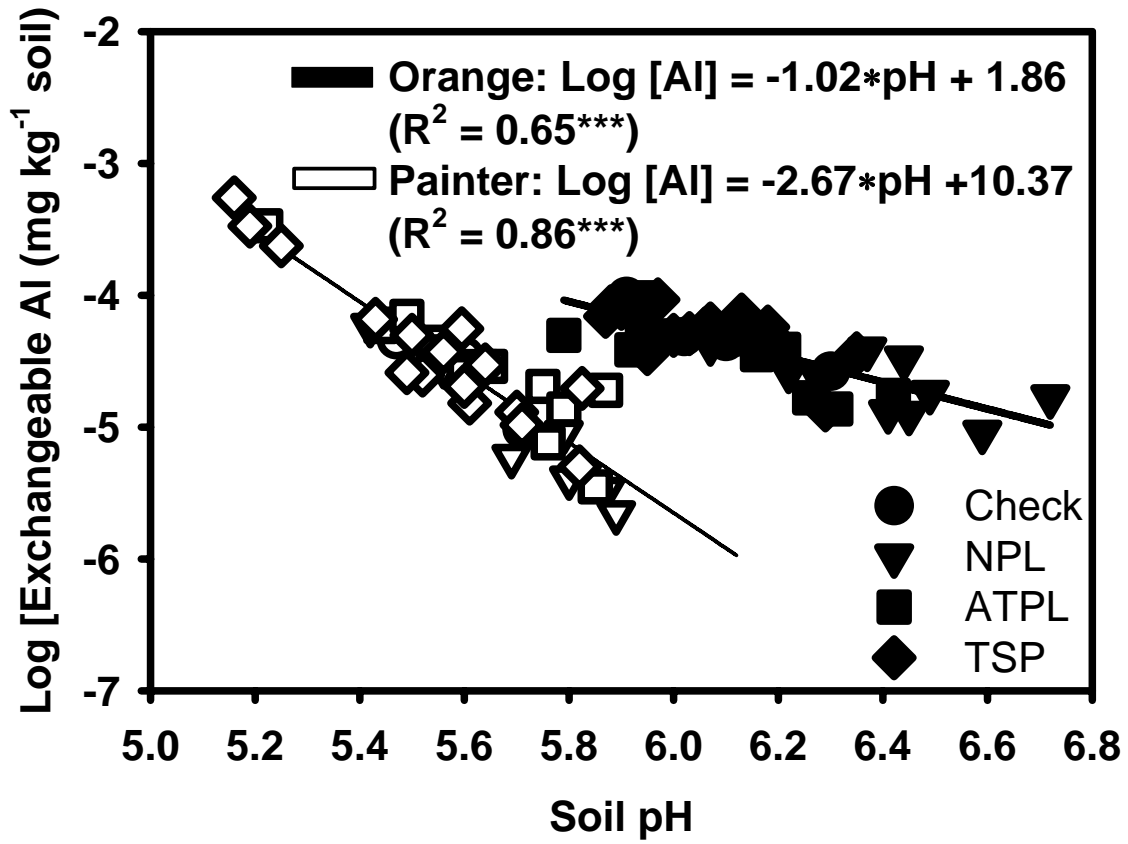
Fig. 2.2: Exchangeable soil Al as a function of soil pH in soils collected at Painter, VA and Orange, VA in the fall of 2002 (***significant at the 0.001 probability level).
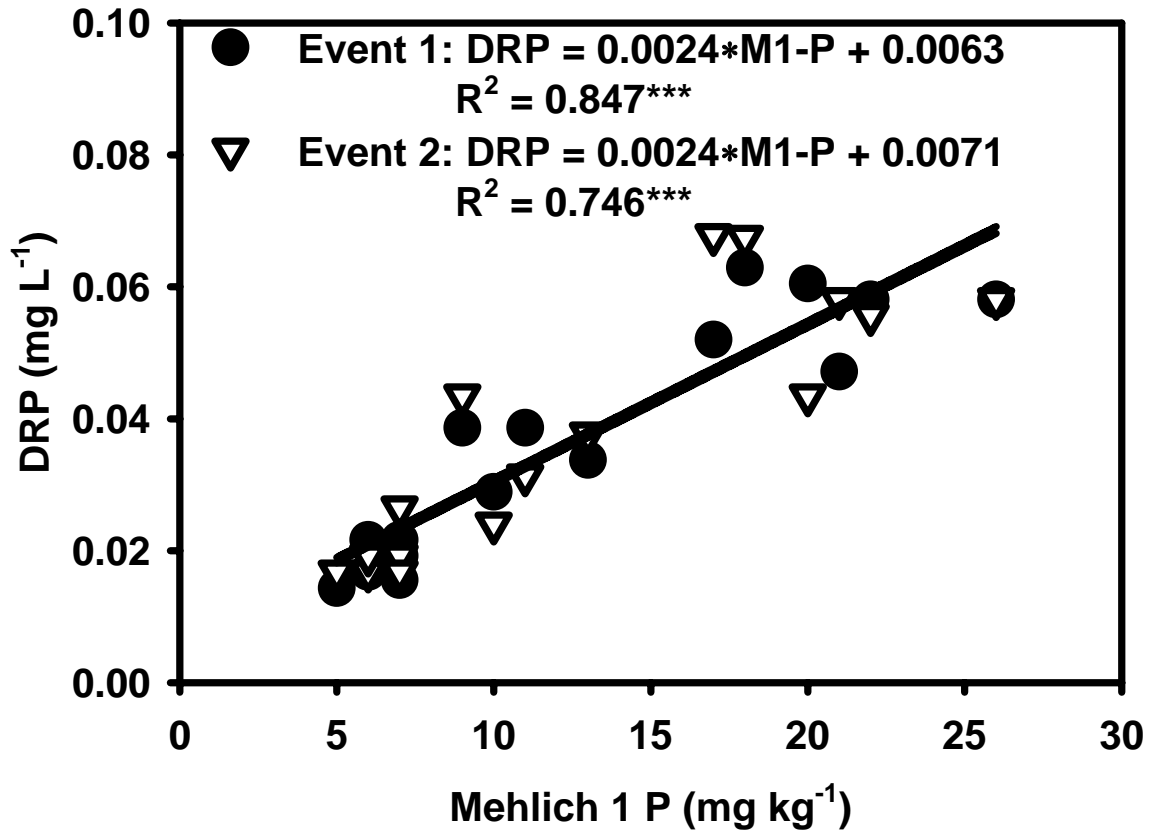
Fig. 2.3: Relationship between the dissolved reactive phosphorus (DRP) found in runoff collected from two rainfall events conducted prior to treatment applications and Mehlich 1 extractable soil phosphorus (M1-P) (** significant at the 0.0001 probability level).

Table 2.1: Three-year average total elemental composition of the alum-treated poultry litter (ATPL) and normal poultry litter (NPL) corrected to a dry weight.

Element	ATPL		NPL	
	mg kg^{-1}	CV†	mg kg^{-1}	CV†
NH$_4$-N	17094	0.19	10625	0.11
Total-N	54651	0.05	44501	0.05
P	16712	0.18	20150	0.10
K	28869	0.09	32004	0.08
Ca	19722	0.34	20529	0.32
Mg	8700	0.29	7808	0.18
S	24578	0.18	6861	0.03
Zn	558	0.07	545	0.07
Cu	694	0.38	798	0.06
Mn	694	0.08	669	0.06
Na	9126	0.12	10006	0.09
Al	8563	0.13	1221	0.13
Al/P ratio	0.51		0.06	

†CV, Coefficient of variation for annual analysis of stockpiled litter.

Table 2.2: Three-year average litter application rates and corresponding P, plant available nitrogen (PAN), NH_4NO_3-N, total PAN, and total N application rates resulting from each treatment combination.

P Source	Rate†	Litter Applied	P Rate	PAN‡ Applied as Litter	Total-N Applied	NH_4NO_3-N Applied	Total PAN‡ Applied
		Mg ha^{-1}	-------------------------kg ha^{-1}-------------------------				
Control	-----	0.0	0	0	173	173	173
Normal litter	NBNL	5.8	116	173	257	0	173
Triple super phosphate	NBNL	0.0	116	0	173	173	173
Alum treated litter	NBAL	4.6	76	173	249	0	173
Triple super phosphate	NBAL	0.0	76	0	173	173	173
Normal litter	CR	1.2	24	36	190	137	173
Alum treated litter	CR	1.5	24	54	197	119	173
Triple super phosphate	CR	0.0	24	0	173	173	173
Normal litter	3CR§	3.6	73	107	227	66	173
Alum treated litter	3CR§	4.4	73	163	249	10	173
Triple super phosphate	3CR§	0.0	73	0	173	173	173

†NBNL, normal litter applied to supply 173 kg plant available N ha^{-1}; NBAL, alum treated litter applied to supply 173 kg plant available N ha^{-1}; CR, P sources applied to supply 24 kg P ha^{-1}; and 3CR, P sources applied to supply 73 kg P ha^{-1} applied once prior to planting in 2000.

‡PAN was estimated to equal 60% of organic N plus 90% of NH_3-N applied in poultry littler.

§3CR treatments received P in 2000 growing season and only NH_3NO_3-N in 2001 and 2002.

Table 2.3: Corn grain yield, ear-leaf N, ear-leaf P, and grain N concentrations at Painter, VA in 2000-2002.

P Source	Rate†	Yield			Ear-leaf N			Ear-leaf P			Grain N		
		2000	2001	2002	2000	2001	2002	2000	2001	2002	2000	2001	2002
		--------Mg ha^{-1}------			--g kg^{-1}--								
Control	-----	13.0	11.0	1.2	21.6	26.4	13.6	2.7	3.0	2.7	13.0	13.6	14.9
Normal litter	NBNL	9.9	7.5	1.4	17.9	20.3	16.6	2.3	2.7	2.9	11.5	11.9	16.8
Triple super phosphate	NBNL	12.7	10.8	1.8	20.8	25.6	20.4	2.8	3.4	3.6	12.4	12.8	16.8
Alum treated litter	NBAL	8.7	6.1	2.1	15.9	19.9	15.6	2.0	2.5	2.4	12.1	11.0	14.7
Triple super phosphate	NBAL	12.3	10.6	2.6	23.5	25.8	20.4	2.8	3.0	3.0	12.2	12.7	16.6
Normal litter	3CR	10.9	10.0	2.1	19.3	25.2	20.8	2.4	3.1	2.9	12.3	12.6	16.7
Alum treated litter	3CR	9.0	10.9	2.1	19.0	24.6	19.4	2.4	3.0	2.7	12.3	13.1	16.5
Triple super phosphate	3CR	12.6	11.1	2.0	23.8	26.0	20.8	3.0	3.0	3.1	12.8	12.2	16.6
	LSD(0.05)	1.5	2.2	NS	3.0	3.5	2.0	0.4	0.4	0.4	NS	1.3	1.3

†NBNL, normal litter applied to supply 173 kg plant available N ha^{-1}; NBAL, alum treated litter applied to supply 173 kg plant available N ha^{-1}; CR, P sources applied to supply 24 kg P ha^{-1}; and 3CR, P sources applied to supply 73 kg P ha^{-1} applied once prior to planting in 2000.

Table 2.4: Monthly rainfall totals and 60 year rainfall averages at Painter, VA and Orange, VA during the 2000-2002 growing seasons.

	Painter				Orange			
	2000	2001	2002	Average	2000	2001	2002	Average
	--------------------------------------cm--							
Apr.	10.0	6.0	12.3	7.8	13.1	1.8	9.1	7.8
May	11.2	10.1	5.7	8.6	5.5	11.9	4.9	9.7
June	9.1	13.4	5.5	8.6	15.1	21.3	7.2	9.4
July	21.1	23.6	14.5	11.4	8.7	10.4	13.2	11.5
Aug.	16.9	5.2	6.9	10.5	6.9	7.6	6.9	10.1
Sept.	12.2	5.8	5.3	9.0	13.0	2.1	6.3	9.4
Total	80.5	64.1	50.2	56.0	62.3	55.1	47.6	57.8

Table 2.5: Average P and N content of corn ear leaves collected during mid-silk in 2001 and 2002 and grain harvested in 2000-2002 at Orange, VA.

P Source	Rate†	Yield	Ear leaves		Grain	
			P	N	P	N
		Mg ha^{-1}	------------------g kg^{-1}------------------			
Control	-----	8.2	2.5	25.5	2.5	13.8
Normal litter	NBNL	8.0	2.5	25.2	2.8	14.0
Triple superphosphate	NBNL	7.9	2.6	25.7	2.7	14.0
Alum treated litter	NBAL	7.8	2.4	25.2	2.8	13.9
Triple superphosphate	NBAL	8.3	2.6	26.7	2.7	14.0
Normal litter	CR	7.8	2.5	26.2	2.6	13.9
Alum treated litter	CR	7.6	2.5	26.5	2.6	13.9
Triple superphosphate	CR	7.7	2.6	26.6	2.5	14.0
Normal litter	3CR	7.8	2.4	25.9	2.5	13.9
Alum treated litter	3CR	8.2	2.4	25.7	2.4	13.7
Triple superphosphate	3CR	8.1	2.6	26.1	2.5	14.0
	LSD(0.05)	NS	NS	NS	0.3	NS

†NBNL, normal litter applied to supply 173 kg plant available N ha^{-1}; NBAL, alum treated litter applied to supply 173 kg plant available N ha^{-1}; CR, P sources applied to supply 24 kg P ha^{-1}; and 3CR, P sources applied to supply 73 kg P ha^{-1} applied once prior to planting in 2000.

Table 2.6: Soil pH and exchangeable Al in soil collected in the fall of 2002 at Painter and Orange, VA.

P Source	Rate†	Painter		Orange	
		pH	Al	pH	Al
			mg kg^{-1}		mg kg^{-1}
Control	-----	5.57	0.94	6.08	1.47
Normal litter	NBNL	5.92	0.08	6.54	0.56
Triple superphosphate	NBNL	5.66	0.76	5.99	1.74
Alum treated litter	NBAL	5.81	0.62	6.19	0.73
Triple superphosphate	NBAL	5.44	3.08	6.05	1.33
Normal litter	CR	5.53	1.20	6.22	0.78
Alum treated litter	CR	5.57	2.72	6.11	1.05
Triple superphosphate	CR	5.52	2.14	6.16	1.37
Normal litter	3CR	5.72	0.45	6.28	0.94
Alum treated litter	3CR	5.62	0.85	6.06	1.75
Triple superphosphate	3CR	5.54	4.09	6.07	1.72
	LSD(0.05)	0.24	NS	0.20	0.62

†NBNL, normal litter applied to supply 173 kg plant available N ha^{-1}; NBAL, alum treated litter applied to supply 173 kg plant available N ha^{-1}; CR, P sources applied to supply 24 kg P ha^{-1}; and 3CR, P sources applied to supply 73 kg P ha^{-1} applied once prior to planting in 2000.

Table 2.7: Total P applied and removed and the resulting net P addition for each treatment during the 3-year studies conducted at Painter and Orange; and the resulting Mehlich 1 soil P (M1-P) and H_2O extractable P (H_2O-P) found in soils collected in the fall of 2002.

P Source	Rate†	Total P Applied	Painter				Orange			
			Total P Removed	Net P addition	M1-P	H_2O-P	Total P Removed	Net P addition	M1-P	H_2O-P
		------------kg ha^{-1}------------			----mg kg^{-1}----		-------kg ha^{-1}-------		----mg kg^{-1}----	
Control	-----	0	74	-74	71	2.5	60	-60	8	0.2
Normal litter	NBNL	348	56	292	147	13.0	65	283	22	0.6
Triple superphosphate	NBNL	348	71	277	150	11.6	63	285	28	0.5
Alum treated litter	NBAL	228	49	179	93	6.0	64	164	15	0.3
Triple superphosphate	NBAL	228	76	152	115	5.6	66	162	20	0.3
Normal litter	CR	73	80	-7	76	4.1	57	17	8	0.2
Alum treated litter	CR	73	69	4	70	3.4	55	19	8	0.2
Triple superphosphate	CR	73	81	-8	94	4.6	57	16	12	0.2
Normal litter	3CR	73	66	7	82	5.1	60	13	9	0.2
Alum treated litter	3CR	73	69	4	86	4.8	65	9	10	0.2
Triple superphosphate	3CR	73	76	-3	80	4.3	59	14	10	0.2
	LSD(0.05)	11	11		21	2.6	6	6	6	0.2

†NBNL, normal litter applied to supply 173 kg plant available N ha^{-1}; NBAL, alum treated litter applied to supply 173 kg plant available N ha^{-1}; CR, P sources applied to supply 24 kg P ha^{-1}; and 3CR, P sources applied to supply 73 kg P ha^{-1} applied once prior to planting in 2000.

Table 2.8: Effect of P source, application rate, and timing of runoff event after P application on P loss, sediment loss and total carbon loss in runoff collected at Orange, VA during simulated rainfall.

P Source	Rate†	DRP	Total P	Sediment	Total Carbon‡
		------mg l^{-1}-----		g l^{-1}	mg l^{-1}
First runoff event, May 2003 (Treatments applied and incorporated approximately 1-year previous)					
Control	-----	0.01	2.0	3.3	NA
Normal litter	NBNL	0.06	1.9	1.4	NA
Triple superphosphate	NBNL	0.05	5.1	14.8	NA
Alum treated litter	NBAL	0.04	4.6	7.5	NA
Triple superphosphate	NBAL	0.06	3.5	11.5	NA
Normal litter	CR	0.02	5.7	13.3	NA
Alum treated litter	CR	0.03	2.2	2.1	NA
Triple superphosphate	CR	0.02	3.2	3.6	NA
	LSD(0.05)	0.01	NS	NS	
Second runoff event, May 2003 (Treatments applied and incorporated approximately 1-year previous)					
Check	-----	0.02	3.2	4.8	NA
Normal litter	NBNL	0.06	2.3	1.9	NA
Triple superphosphate	NBNL	0.06	5.1	12.2	NA
Alum treated litter	NBAL	0.04	3.9	4.0	NA
Triple superphosphate	NBAL	0.06	5.7	9.8	NA
Normal litter	CR	0.02	4.8	10.6	NA
Alum treated litter	CR	0.03	2.8	2.6	NA
Triple superphosphate	CR	0.02	3.7	5.4	NA
	LSD(0.05)	0.02	NS	NS	
Third runoff event, Aug. 2003 (Treatments were applied without incorporation 2-days previous)					
Control	-----	0.0	0.9	1.4	22
Normal litter	NBNL	78.0	103.7	2.3	620
Triple superphosphate	NBNL	73.2	73.5	2.6	30
Alum treated litter	NBAL	30.5	96.3	3.5	906
Triple superphosphate	NBAL	53.1	58.4	1.3	38
Normal litter	CR	19.7	24.6	2.3	227
Alum treated litter	CR	5.7	16.8	1.0	141
Triple super phosphate	CR	10.3	15.8	2.5	41
	LSD(0.05)	4.5	13.7	1.4	54
Fourth runoff event, Aug. 2003 (Treatments were applied without incorporation 3-days previous)					
Control	-----	0.0	0.9	1.2	18
Normal litter	NBNL	6.4	9.5	0.6	76
Triple superphosphate	NBNL	2.2	14.1	3.0	53
Alum treated litter	NBAL	1.0	5.7	1.0	79
Triple superphosphate	NBAL	4.4	8.4	1.9	30
Normal litter	CR	0.7	2.8	1.3	33
Alum treated litter	CR	0.3	1.5	0.6	25
Triple superphosphate	CR	0.3	3.6	2.8	37
	LSD(0.05)	0.6	8.2	NS	NS

†NBNL, normal litter applied to supply 173 kg plant available N ha^{-1}; NBAL, alum treated litter applied to supply 173 kg plant available N ha^{-1}; CR, P sources applied to supply 24 kg P ha^{-1}; and 3CR, P sources applied to supply 73 kg P ha^{-1} applied once prior to planting in 2000.

‡NA, not analyzed, total carbon was not determined for runoff collected in the first and second runoff events.

Chapter 3: Alum-Treated Poultry Litter as a Nutrient Source for Tall Fescue and its Effect on Soil Phosphorus Status

Abstract

The purpose of this 4-year study was to evaluate alum-treated poultry litter (ATPL) as a nutrient source for tall fescue (*Festuca arundinacea* L.) and the resulting changes in soil P status. Plots were established in the spring of 2000 at Orange, VA, on a Davidson loam (fine, kaolinitic, thermic Rhodic Kandiudult). Treatments included the application of ATPL, non-treated poultry litter (NPL) and triple superphosphate (TSP) at rates based on current litter management strategies in Virginia. During the four years of this study, applications of ATPL resulted in forage yield and P uptake similar to that found in treatments receiving NPL. Also, no significant differences in Mehlich 1 extractable soil P between litter treatments were observed after four years of application. A soil P fractionation procedure revealed significantly decreased H_2O extractable inorganic P (Pi) concentrations in soils receiving N-based rates of ATPL compared to equivalent applications of NPL. Conversely, the organic P (Po) fraction extracted with 0.1 *M* NaOH was significantly elevated in treatments that had received ATPL compared to those receiving NPL or TSP regardless of P application rate. These results show that ATPL does not adversely affect P uptake by fescue or forage production. This study also shows that ATPL can have an impact on the forms of P found in soils following continued applications; however, these differences may not be detected through routine soil analyses such as the Mehlich 1 extraction.

Abbreviations:

ATPL: Poultry litter treated with alum

2CR: Phosphorus application rate of 70 kg P ha^{-1}, equivalent to estimated 2-years of crop P removal, applied prior to planting in 2000 and 2002

CR: Phosphorus application rate of 35 kg P ha^{-1}, equivalent to estimated crop P removal.

NBAL: Phosphorus rate supplied by the N-based alum-treated poultry litter application of 112 kg PAN ha^{-1}

NBNL: Phosphorus rate supplied by the N-based non-treated poultry litter application of 112 kg PAN ha^{-1}

NPL: Non-treated poultry litter without alum additions.

PAN: Plant available N

Pi: Inorganic P

Po: Organic P

TSP: Triple superphosphate fertilizer

Introduction

Non-point source phosphorus (P) addition to surface water bodies continues to be a significant contributor to water quality impairment (Commonwealth of Virginia, 2005) through its role as a contributor to the eutrophication of sensitive water bodies (Sharpley et al., 1994; Carpenter et al., 1998). A significant portion of this P originates from surface runoff from agricultural fields in the form of dissolved and sediment-bound P.

Historic applications of animal manures, such as poultry litter, at rates in excess of crop removal have resulted in elevated concentrations of P in agricultural soils (Kingery et al., 1994; Sharpley et al., 1993), specifically in those soils proximate to concentrated animal production facilities that have received long-term applications of P in animal wastes. These increases in soil P can correspond to increased concentrations of P in surface water runoff (Sharpley, 1995; Pote et al., 1996). Also, the timing, method and rate of P application can have profound impacts on the amount of P lost from agricultural land receiving poultry litter applications (Sharpley et al., 1994). Therefore, land managers are currently encouraged through regulatory or cost share programs to decrease litter application rates and incorporate conservation tillage into their land management strategies. However, decreased litter application rates increase the land base required for utilization/disposal of poultry litter. In areas of intensive poultry production, transportation costs associated with dispersing litter to lands located farther from production facilities can become prohibitive. In addition, conservation tillage practices such as no-till, reduce P losses associated with litter particle loss and soil erosion; however, they have the potential of increasing soluble P losses (Sharpley et al., 1994). An alternative management strategy is chemical alteration of poultry litter to reduce soluble P concentrations.

Various chemical amendments have been evaluated as to their effectiveness in reducing soluble P concentrations in poultry litter. Many of these amendments have included Ca, Al, and Fe containing compounds such as alum ($Al_2(SO_4)_3 \bullet 16H_2O$), ferrous sulfate ($FeSO_4 \cdot 7H_2O$) (Shreve et al., 1996), sodium aluminate ($Na_2Al_2O_4$), quicklime (CaO), slaked lime [$Ca(OH)_2$], calcitic limestone ($CaCO_3$), dolomitic limestone [$CaMg(CO_3)$], gypsum ($CaSO_4 \cdot 2H_2O$), ferrous chloride ($FeCl_2 \cdot 4H_2O$), ferric chloride ($FeCl_3$), and ferric sulfate [$Fe_2(SO_4)_3 \cdot 2H_2O$] (Moore and Miller, 1994). Of these amendments, alum has been found to be one of the most cost-effective options (Moore et al., 1999). Initial laboratory evaluation of alum as a poultry litter amendment revealed that additions of alum at rates of 100 g kg^{-1} could reduce the concentration of soluble P by 75% (Moore and Miller, 1994; Shreve et al., 1996). A subsequent large farm-scale evaluation of alum as a litter amendment confirmed these findings (Sims and Luka-McCafferty, 2002). Sims and Luka-McCafferty (2002) applied alum to 97 houses at a rate of 0.09 kg alum m^{-2} flock^{-1}. This rate was estimated to be equivalent to that required to result in a final litter containing 10% alum by weight if previous litter was not present in the house at the time of application. However, the houses included in this study varied widely in the amount of litter present at the initiation of the study. Despite this variation in litter thickness, applications of alum resulted in an average decrease in soluble P of 72% compared to that in litter collected from 97 poultry houses not receiving the alum treatment.

Various studies have focused on evaluating the mechanisms by which this reduction in P solubility resulting from alum treatment of poultry litter is achieved. X-ray adsorption near edge structure spectroscopy analysis was used to determine that in NPL, P was present as weakly bound inorganic and organic P with some Ca-phosphate compounds present (Peak et al., 2002). Analysis of ATPL suggested that the alum applied to the litter precipitates as amorphous $Al(OH)_3$ to which inorganic P was adsorbed. Further investigation into the speciation of P in poultry litter using solid-state ^{31}P nuclear magnetic resonance (NMR) spectroscopic analysis found the presence of a complex mixture of organic and inorganic orthophosphates (Hunger et al., 2004). This analysis again revealed a Ca-P phase, which the researchers attributed to a surface precipitate on $CaCO_3$ in both ATPL and NPL. They also found P associated with Al only in the ATPL and stated that this was likely a mixture of poorly ordered wavellite and surface complexes with $Al(OH)_3$.

This reduction in the soluble P concentration in ATPL has been shown to result in decreased runoff P concentrations of soluble P following surface application. Smith et al. (2004) found that ATPL applications resulted in 47 to 74 % reductions in soluble P concentrations in runoff compared to NPL depending on dietary treatment. Warren et al. (2006) also found that N-based applications of ATPL for conventionally tilled corn (*Zea mays* L.) production resulted in 61% reductions in runoff concentrations of soluble P compared to equivalent applications of NPL. Alum-treated poultry litter applications also resulted in 63 to 87% reductions in P concentrations in runoff compared to NPL when applied to fescue pasture (Shreve et al., 1995).

Despite this collection of data evaluating the use of alum as a poultry litter amendment, there is only limited data evaluating the effects of long-term applications of ATPL on the solubility and forms of P in soils. Initial laboratory incubation evaluations found that after 294 days the soluble P concentrations in soils treated with ATPL were significantly reduced compared to those found in soils treated with NPL (Shreve et al., 1996). Warren et al. (2006) found that N-based applications of ATPL to field corn resulted in lower soil P status compared to that found in treatments receiving equivalent N-based applications of NPL both in the Coastal Plain and Piedmont regions of Virginia. In Coastal Plain soils, the reduced P status could be attributed to reduced P application rates, and also to decreased availability of the applied P. Moore et al. (1998) also presented soil data collected after 3 years of ATPL application to tall fescue which showed lower concentrations of both Mehlich 3 and H_2O extractable P in soils receiving ATPL compared to those receiving NPL even when both were applied at similar P rates.

Data evaluating speciation of P in soils after applications of ATPL were presented by Staats et al. (2004) who incubated three soils with ATPL and NPL for 25 days and then performed the sequential fractionation of Chang and Jackson (1957) on the soils. They found little difference in the distribution of P among soils treated with ATPL compared to those treated with NPL. In fact, the only significant difference among the litter sources was found in the NH_4F extraction, in which P concentrations were elevated in soils receiving ATPL compared to those receiving NPL. Elevated P in NH_4F extractions likely resulted from the increased association of P with Al in soils treated with the ATPL. Despite this limited laboratory incubation data evaluating P speciation in soils

treated with ATPL, nothing is known about the long-term effects of ATPL applications on the distribution of P in soils under crop production.

The objectives of this study were to evaluate ATPL as a nutrient source for tall fescue hay production and evaluate how long-term applications of ATPL affect P distribution in amended soils. The responses of forage yield and P removal to ATPL applications based on current litter management strategies were evaluated. Also, changes in the chemical distribution of soil P resulting from these applications of ATPL were evaluated using sequential fractionation (Tiessen and Moir, 1993).

Materials and Methods

A replicated small-plot field experiment using fescue grass for hay production was conducted at Virginia Tech's Northern Piedmont Agricultural Research & Extension Center in Orange, Va. The soil at this site was a Davidson loam (fine, kaolinitic, thermic Rhodic Kandiudult). The fescue grass was established through seed planting in the fall of 1999. Individual plots were 2.4 by 4.6 m and treatments were arranged in a randomized complete block design with three replications per treatment.

Phosphorus sources used in this study consisted of commercial phosphate fertilizer (triple superphosphate (TSP)), alum-treated poultry litter (ATPL) and non-treated poultry litter (NPL), each applied at 4 different P rates (Table 1). In addition to a no-P check treatment, P rates were based on: (1) applying NPL at rates to meet the N needs of the crop (NBNL); (2) applying ATPL at rates to meet the N needs of the crop (NBAL); (3) annual estimated crop removal of P (CR); (4) estimated 2-year crop removal of P (2CR) and (5) soil test P recommendations (STP). Treatments received 112 kg plant available N (PAN) ha^{-1} as poultry litter and/or NH_4NO_3. However, the 2CR P application rate did result in PAN application rates in excess of this target N rate for the application of ATPL in 2000 and for both litter sources in 2002 (Table 2). The 112 kg PAN ha^{-1} application rate was chosen to provide sufficient N for an expected yield of 9.0 Mg ha^{-1} assuming a requirement of 12.5 kg PAN Mg^{-1} of forage (Virginia Department of Conservation and Recreation, 1995). The availability of N in the NPL and ATPL was estimated using guidelines developed by the Virginia Department of Conservation and Recreation (Virginia Department of Conservation and Recreation, 1995). These guidelines assume that 50 % of the NH_4-N and 60 % of the organic-N is available as PAN for crop uptake in the year of application when litter is surface applied without incorporation. The application rates of litter, PAN, and P resulting from the treatment structure are outlined in Table 1. These treatments and supplemental N were broadcast-applied in the spring of each growing season. Supplemental K fertilizer was supplied as fertilizer grade KCl to treatments at rates determined by Virginia Cooperative Extension soil test recommendations to insure adequate K availability for all treatments.

These recommendations were determined through Mehlich 1 extractions of soils (Kuo, 1996) collected prior to treatment applications. Agricultural lime was applied at a rate of 5.6 Mg ha^{-1} to all plots prior to applying annual treatments in the spring of 2001.

Poultry litter applied in the spring of 2000 was collected from two poultry houses included in the study presented by Sims and Luka-McCafferty (2002). One of the houses received alum at an approximate rate of 0.09 kg bird^{-1} prior to the introduction of each

flock. The second house received no alum additions. Poultry litter applied in the spring of 2001 through 2003 was collected from two poultry houses located side by side under similar management in the Shenandoah Valley of Virginia. One of the houses received alum at an approximate rate of 0.05 kg bird[-1] prior to the introduction of each flock. The second house received no alum additions. Litter was collected at the end of a grow-out and stored under cover until application. The average elemental compositions of the litters are presented in Table 2. The analyses were conducted by the University of Maryland Soil Testing Laboratory for the 2000 and 2001 growing seasons and by the Agricultural Service Laboratory, Clemson University, for the 2002 and 2003 growing season.

Forage yields were determined by harvesting a 1.5 by 4.6 m area of each plot as needed using a forage harvester. Subsamples of forage from each harvest were collected for moisture determination and chemical analysis after drying at 65 °C. Plant tissue samples were ground to pass a 1.6-mm sieve and digested using a nitric acid and peroxide digestion procedure (Jones and Case, 1990) and analyzed for P and Al using a SpectroFlame Modula Tabletop ICP-AES, Spectro Instruments, Fitchburg, MA.

Composite soil samples were collected 12 months after each application of the annual treatments to a depth of 10 cm. Soil samples were air dried, ground, sieved to pass a 2-mm sieve, and analyzed for Mehlich 1 soil test P, exchangeable Al (1:5 soil to 1 N KCl ratio) (Bertsch and Bloom, 1996), and pH (1:1 soil to water ratio) (Thomas, 1996). In addition, samples collected in the spring of 2004 were analyzed for ammonium oxalate extractable P, Fe, and Al (Pote et al., 1999) and subjected to a P fractionation procedure modified from Tiessen and Moir (1993). The first extraction was accomplished by weighing 0.5 g of soil into a 50-mL centrifuge tube, adding 30 mL of deionized H_2O, and shaking overnight (16 h). The suspension was centrifuged at 2000 rpm (1,200 x G) for 30 min. The supernatant was then filtered through a 0.45-μm filter and the particles on the filter were washed back into the centrifuge using 0.5 M $NaHCO_3$. Additional 0.5 M $NaHCO_3$ was added to bring the final volume to 30-mL and this suspension was shaken overnight. This protocol of extraction was used for the 0.5 M $NaHCO_3$ and also carried out for the 0.1 M NaOH and 1.0 M HCl. The remaining soil residue was mixed with 10 mL of concentrated HCl and heated in an 80°C water bath for 10 min. After removal from the water bath an additional 5-mL of concentrated HCl was added and the mixture was allowed to cool. This suspension was centrifuged at 2000 rpm for 30 min and the supernatant decanted without filtration. The remaining soil residue was transferred to 75-mL digestion tubes using deionized H_2O. The soil residue was digested using a mixture of H_2SO_4 and H_2O_2 at 360°C.   Total P was determined on each of the above described extractions using atomic emissions spectroscopy with a SpectroFlame Modula Tabletop ICP-AES, Spectro Instruments, Fitchburg, MA. Inorganic P (Pi) was determined on the H_2O, $NaHCO_3$, and NaOH extractions after acidification and on the concentrated HCl extraction after neutralization using the Molybdate blue method of Murphy and Riley (1962). The organic P (Po) was calculated as the difference between the total P and Pi.

Analysis of variance and contrast analysis were performed using the SAS PROC GLM procedure (SAS Institute, 2001), to determine significant treatment effects on measured response variables. Fisher's protected LSD was used to separate treatment means. Regression analyses were conducted using the SAS PROC REG procedure.

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Results and Discussion

Crop responses

Forage yield was significantly affected by treatment only in the first year of the 4-year study (Table 3). During the 2000 growing season yields from both litter sources were significantly lower than yields obtained from those treatments receiving TSP and commercial inorganic N fertilizer. Although the initial Mehlich 1 extractable P concentration in this soil was 7 mg kg^{-1}, which places it in the medium minus category for the Virginia soil test calibration (Donohue and Heckendorn, 1994), these yield reductions are likely not a result of inadequate P availability because the 0-P check treatment also resulted in a significantly greater yield than did those treatments receiving either poultry litter source. The suppressed yields in treatments receiving poultry litter could be the result of damage to the young fescue grass resulting from litter applications. These suppressed yields did result in significantly lower P removal at the N-based and 2CR treatments compared to that found in treatments receiving TSP.

Despite decreased yields in litter treatments during the 2000 growing season P removal was consistently, although not always statistically, higher in treatments receiving either litter sources compared to the 0-P check treatment for the remainder of the study. A significant response to P applications was observed in the 2003 crop year. Although significant differences were not found among yields, P removal was significantly suppressed in the 0-P check treatment compared to the remaining treatments, while P removal was significantly increased in treatments receiving NPL at the N-based and CR P rates compared to ATPL (Table 3). However, no differences in P removal were found when comparing ATPL to equivalent rates of TSP (Table 3). These data suggest that although alum treatment has been shown to reduce the solubility of P in poultry litter, it did not result in reduced P availability resulting in suppressed yields when surface applied to tall fescue in this study. In fact, when total P removal is evaluated over the 4-year study no significant differences in P removed were found among sources at a given P application rate (Table 4).

These findings are similar to those reported by Warren et al. (2006) who found no significant difference in the P status of corn grown on a Davidson loam when ATPL, NPL or TSP were applied as P sources. Shreve et al. (1995) found that applications of ATPL and NPL when applied at 11.2 Mg litter ha^{-1} resulted in fescue forage yields of 2358 and 1847 kg ha^{-1} with P removal rates of 15.3 kg ha^{-1} and 13.5 kg ha^{-1}, respectively. These researchers attributed the increased yield and subsequent P removal in treatments receiving ATPL to the elevated rate of N applications that resulted from decreased NH_3 volatilization in the poultry production facilities as demonstrated by Moore et al. (1995). However, Smith et al. (2004) found no significant difference in forage P removal by fescue treated with ATPL compared to that treated with NPL. The data collected at Orange further confirm this previous research demonstrating that ATPL performs similarly to NPL as a P source for crop production.

Soil P status

Mehlich 1 extractable P concentrations in soils collected in the spring of 2004 were elevated in all treatments compared to that found in the 0-P check treatments (Table 4).   Also, the N-based treatments resulted in significantly increased Mehlich 1 extractable P compared to the 2CR and CR P application rates. No significant differences in Mehlich 1 extractable P were found among treatments receiving ATPL and NPL.

These results are inconsistent with previous research that reported consistently lower soil test P in soils receiving ATPL (Warren et al., 2006; Moore et al., 1999). Warren et al. (2006) found that each kg of net P ha^{-1} applied as NPL to a Davidson loam soil increased Mehlich 1 P by 0.041 mg P kg^{-1}. In contrast, each kg of net P ha^{-1} applied as ATPL increased Mehlich 1 P by 0.031 mg P kg^{-1}. In the fescue study, the N-based applications of NPL and ATPL resulted in increases in Mehlich 1 extractable P at rates of 0.055 and 0.057 mg P kg^{-1} of soil per kg net P ha^{-1} applied, respectively. These increases per unit of net P applied are slightly higher than that found at the CR application rate which averaged across source was 0.052 mg P kg^{-1} of soil per kg net P ha^{-1}. The inconsistencies between data presented here and in previous research may be explained by the smaller difference between the net P applied as ATPL and NPL in this study (Table 4) compared to that applied to corn by Warren et al. (2006). Net applications of P at N-based rates during the 3-year corn trial conducted by Warren et al. (2006) totaled 283 and 164 kg P ha^{-1} for NPL and ATPL, respectively, whereas during this 4-year fescue study net P applications were 181 and 145 kg P ha^{-1} for NPL and ATPL, respectively (Table 4). The lower P application rates specifically in the NPL treatments, compared to those presented by Warren et al. (2006) do not appear to have been sufficient to result in significant differences in the Mehlich 1 extractable P found between treatments receiving the two litter sources at N-based rates. Also the Al to P ratio for ATPL used in this study was lower at 0.5 compared to that used by Moore et al. (1999) which had an Al to P ratio of approximately 1.0.

Ammonium oxalate extractable P was elevated in the N-based treatments compared to the treatments receiving P at the CR and 2CR rates (Table 4). In addition ammonium oxalate-extractable P was significantly increased in soils receiving ATPL compared to that found in soils receiving NPL (Table 4). However, no significant differences were found when comparing TSP to either of the litter P sources. These are unique data since currently no published data exist that evaluate the effects of ATPL applications on ammonium oxalate-extractable P in soils. A reasonable explanation for the elevated ammonium oxalate-extractable P in soils receiving ATPL is that the treatment of litter with alum results in the formation of Al-P complexes. These complexes are likely amorphous Al-oxides with adsorbed or occluded P (Hunger et al., 2004; Peak et al., 2002). Because P removal during the 4-year study was similar for ATPL and NPL treatments (Table 4), it can be hypothesized that plant P uptake preferentially utilized P forms which were more available than those associated with the amorphous Al complexes formed in ATPL. Therefore, these Al-P forms apparently accumulated in the surface of soil treated with ATPL and are extractable with ammonium oxalate. It should be noted that the applications of ATPL, which resulted in a 4-year cumulative Al application of 106 kg Al ha^{-1}, did not significantly change the ammonium

oxalate-extractable Al (Table 4). This is no surprise because, assuming that the bulk density of the Davidson soil collected at Orange is 1.4 g cm^{-3}, the average ammonium oxalate-extractable Al in the 10 cm depth of soil sampled was 2507 kg ha^{-1}. Therefore the Al applied in the ATPL is less than 5 % of the ammonium oxalate-extractable Al inherently present in the soil.

P Fractionation

The concentrations of Pi extracted using dionized H$_2$O, 0.5 M NaHCO$_3$, and 0.1 M NaOH from soils collected in the spring of 2004 were significantly affected by treatment (Table 5). No significant differences were found in the 1.0 M HCl extractable P, which had an average concentration among treatments of 44 mg P kg^{-1}. Also, there were no significant treatment effects on the concentrations of Pi and Po found in the concentrated HCl extractions nor the concentrations of P found in the H$_2$SO$_4$ digestions. The average concentrations of Pi and Po in the concentrated HCl extraction were 181 and 41 mg P kg^{-1}, respectively. The average concentration of P found in the H$_2$SO$_4$ digestion was 233 mg P kg^{-1}. These results are similar to those found by Blake et al. (2003) who used a similar fractionation procedure to evaluate soil P forms after long-term P applications and removal. They found that 68 to 89 % of the changes in soil P after P applications were in the resin (highly labile), 0.5 M NaHCO$_3$, and 0.1 M NaOH extractions combined with limited changes in the acid-extractable fractions. However, sequential fractionation of NPL has shown that 25 % of the total P found in the litter was in the 1.0 M HCl extraction and less than 2 % was present as residual P extracted by hot acid digestion (Dou et al., 2000). Furthermore, Hunger et al. (2005) used the same fractionation procedure on ATPL and found that 37 to 39 % of P in the litter was extracted using 1.0 M HCl extraction. However, the soil fractions presented here show that litter applications to the Davidson soil were not sufficient to increase the acid-soluble soil P, as evident by the lack of a significant increase in the 1.0 M HCl extractable fraction compared to the 0-P check treatment.

Mean separation revealed that differences in Pi extracted with deionized H$_2$O were found among sources only at the N-based rates (Table 5). In fact the CR and 2CR P applications were not sufficient to significantly increase this fraction above that found in the 0-P check treatment. At the N-based rates, both TSP treatments significantly increased H$_2$O extractable Pi compared to the two litter sources. Also, the N-based ATPL treatment resulted in significantly lower H$_2$O extractable Pi compared to the equivalent NPL treatment, and was not significantly elevated above that found in the 0-P check treatment. These findings are in agreement with previous research conducted by Moore et al. (1999) who also found that after 4 yrs of application to fescue, ATPL treatments resulted in significantly lower H$_2$O extractable Pi compared to that found in NPL treatments. Warren et al. (2006) also found that H$_2$O extractable P, as determined by the Molybdate blue method (Murphy and Riley, 1962), was 50% lower in treatments receiving N-based applications of ATPL (76 kg P applied ha^{-1}) compared to equivalent N-based applications of NPL (116 kg P applied ha^{-1}). However, Warren et al. (2006) showed no difference in the H$_2$O extractable P between treatments receiving TSP verses ATPL when both were applied at an N-based rate, which supplied 76 kg P ha^{-1}. This lack of significant differences in H$_2$O extractable Pi was thought to result from the lower

pH and subsequently higher concentrations of exchangeable Al found in the treatment receiving TSP. The pH of soils collected from the fescue experiment in the spring of 2004 was not significantly affected by treatment and the average pH across treatments was 6.7. Likewise, exchangeable Al concentrations in the soils collected in the spring of 2004 were not affected by treatments, with an average value of 0.15 mg Al kg^{-1}.

The concentrations of Pi found in the 0.5 M NaHCO$_3$ extracts were elevated in all treatments receiving P applications compared to the 0-P check treatment (Table 5). No significant differences among the CR and 2CR P treatments were found. However, each of the N-based treatments elevated this fraction compared to the CR and 2CR P treatments (Table 5). Within the N-based application rates, both TSP treatments significantly increased 0.5 M NaHCO$_3$-extractable Pi compared to that found in the two litter treatments. Also, the N-based NPL application resulted in a significant increase in the 0.5 M NaHCO$_3$ extractable Pi compared to that found in the equivalent ATPL treatment.

The concentrations of Pi extracted using 0.1 M NaOH were not significantly increased by the CR or 2CR P application of any source compared to the 0-P check treatment (Table 5). However, each of the N-based treatments significantly increased the 0.1 M NaOH extractable Pi compared to the 0-P check treatment. Within the N-based treatments, the application of TSP at the NBNL rate significantly increased the 0.1 M NaOH extractable Pi compared to the remaining N-based treatments with no other significant differences among sources.

In addition to these changes in Pi, significant differences were found in the Po extracted with 0.1 M NaOH (Table 5). Applications of ATPL resulted in significant increases in the concentrations of Po extracted with 0.1 M NaOH compared to the 0-P check treatment, regardless of rate. However, applications of TSP and NPL did not increase this fraction of P above that found in the 0-P check treatment and this fraction is consistently lower in these treatments compared to ATPL treatments.

.   Although limited data are available on the effects of ATPL on soil P fractions, litter fractionation studies are available for comparison. Dou et al. (2003) evaluated the effects of adding 100 g alum kg^{-1} of litter on the sequential fractionation of P in litter. They found that alum additions resulted in decreases in the H$_2$O extractable and 1.0 M HCl extractable Pi with corresponding increases in Pi extracted using NaHCO$_3$ and 0.1 M NaOH. In addition, the authors noted much higher concentrations of Po in the 0.1 M NaOH extraction of ATPL compared to that found in NPL. The authors attributed this increase in Po to the sorption-entrapment of organic P on Al(OH)$_3$ flocs which were said to form as a result of alum addition to poultry litter. This helps to explain the elevated 0.1 M NaOH extractable Po found in soils treated with ATPL.   The elevated concentrations of this fraction in both ATPL, as demonstrated by Dou et al. (2003) and in soils receiving ATPL, suggest that this 0.1 M NaOH extractable Po may contain P compounds that are stable in the soil environment. The fact that this fraction is elevated not only in the N-based ATPL treatment but also in the 2CR ATPL treatment, which had not received litter applications for 2 years prior to the spring 2004 soil collection, suggests that the 0.1 M NaOH extractable Po fraction is relatively stable in soils. Of course there is likely a mechanism by which the accumulation of this fraction in soils receiving ATPL is regulated. The lack of a significant increase in the 0.1 M NaOH-

extractable Po found in the treatment receiving N-based applications of ATPL compared to that found in treatments receiving ATPL at the CR and 2CR application rates supports the presence of this regulatory mechanism. This mechanism may be related to the cycling of organic matter within the soil system. Future research may focus on whether such a mechanism exists as well as focus on the persistence of this soil P fraction.

The lack of significant difference in the concentrations of 0.1 M NaOH extractable Pi when comparing ATPL and NPL treated soils can be attributed to the mineral character of the soil. As mentioned previously, the amount of Al added as ATPL will at best increase the amorphous Al content of the soil by less than 5%. Therefore, the inherent mineral character of this soil will play a greater role in controlling 0.1 M NaOH-extractable Pi, which is described as stable Pi associated with Fe and Al (Hedley et al., 1982), than will the addition of ATPL.

It should also be noted again that ammonium oxalate-extractable P was elevated in soils receiving ATPL treatments. In fact when regression analysis was used to correlate ammonium oxalate P with individual P fractions or combinations of the P fractions, correlation coefficients were optimized when comparing ammonium oxalate P to the summed concentration of Pi found in the H_2O, 0.5 M NaHCO$_3$, and 0.1 M NaOH extractions plus the Po extracted using 0.1 M NaOH (Fig. 1). This demonstrates that ammonium oxalate extractable P is associated with not only the biologically available Pi extracted using H_2O and 0.5 M NaHCO$_3$ and the more stable Pi associated with amorphous material extracted with 0.1 M NaOH (Hedley et al., 1982), but also Po extracted with 0.1 M NaOH. The comparisons of ammonium oxalate-extractable P to the fractionation data suggest that the elevated concentrations of 0.1 M NaOH-extractable Po may account for elevated ammonium oxalate-extractable P concentrations found in soils treated with ATPL.

Linear correlation of Mehlich 1 extractable P with the various P fractions shows high correlation with the Pi found in both H_2O and 0.5 M NaHCO$_3$ extracts (Fig. 2). In fact, the sum of the concentrations of Pi extracted using H_2O and 0.5 M NaHCO$_3$ was best related to the Mehlich 1 extractable P (Fig. 2). This is in agreement with previous work that has described 0.5 M NaHCO$_3$ extractable Pi as biologically available P (Sharply, 1996; Hedley et al., 1982; Tiessen and Moir, 1993).

Conclusions

As a P source for tall fescue forage production, ATPL performed similarly to NPL. The data presented are unique because the Davidson soil used in this study contained moderate to low levels of soil test P. Data from this study demonstrate that although the treatment of poultry litter with alum reduces the solubility of P in the litter, it may not adversely affect its availability for crop uptake. Of course the application of ATPL to tall fescue did not result in significantly lower concentrations of Mehlich 1 soil test P compared to equivalent applications of NPL. Despite the lack of significant differences in Mehlich 1-extractable P, sequential P fractionation of treated soils revealed significant changes in the forms of P found in soils receiving ATPL compared to those receiving NPL. The concentrations of Pi extracted using H_2O and 0.5 M NaHCO$_3$ were lower in treatments receiving ATPL at the N-based rate compared to those found in

treatments receiving equivalent rates of NPL. Therefore it appears that the Mehlich 1 extraction was not sensitive enough to detect these differences in the availability of P in soils treated with the two litter sources. However, it should be pointed out that there was a strong correlation between these two soil fractions and Mehlich 1 extractable P. It is likely that continuation of the current rates of P applications would result in significant deviation in the Mehlich 1 extractable P found in treatments receiving the two litter sources.

The decreases in H_2O-extractable and 0.5 M $NaHCO_3$-extractable Pi as a result of ATPL applications were accompanied by increases in the concentrations of Po extracted using 0.1 M NaOH. Unlike the suppressed concentrations of Pi extracted using H_2O and 0.5 M $NaHCO_3$, which only occurred in the N-based application of ATPL, the increase in 0.1 M NaOH-extractable Po occurred at each application rate.   The data show that this P fraction is persistent after ATPL application to soil as evident by the elevated concentration of this P fraction in the 2CR treatments that had not received ATPL for 2 years prior to sampling soils in spring 2004.   Although the 0.1 M NaOH-extractable Po does appear to persist in soil treated with ATPL, it did not increase as the rate of ATPL application increased, which suggests the presence of mechanisms that limit the accumulation of 0.1 M NaOH-extractable P in soils. Future research may focus on identifying the P forms found in this fraction and evaluation of the mechanisms which control the accumulation of this P fraction in soils receiving ATPL in order to better understand the mechanisms by which alum treatment of poultry litter affects soil P distribution. The presence of the 0.1 M NaOH-extractable Po fraction did help to explain the elevated ammonium oxalate extractable P concentrations found in the ATPL treatments. Again, it is important that future research evaluate the availability of the 0.1 M NaOH-extractable P fraction to surface water runoff losses in order to ensure that the treatment of poultry litter with alum is an effective management practice for long-term reductions in the transport of P from agricultural systems.

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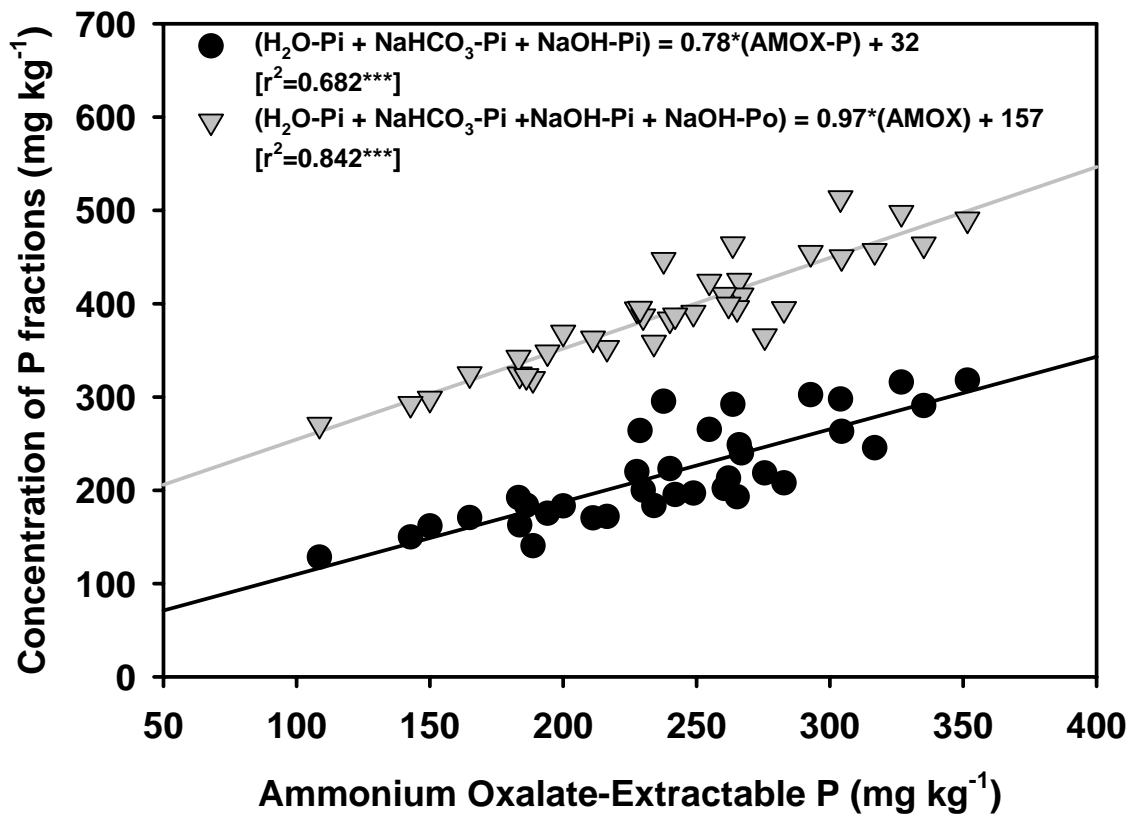
Fig. 3.1: The summed concentrations of inorganic P extracted using deionized H_2O (H_2O-Pi), 0.5 M NaHCO$_3$ (NaHCO$_3$-Pi), 0.1 M NaOH (NaOH-Pi), and organic P extracted using 0.1 M NaOH (NaOH-P0) in relation to ammonium oxalate extractable P(AMOX-P) measured in soils collected in the spring 2004 (***, p value <0.0005).
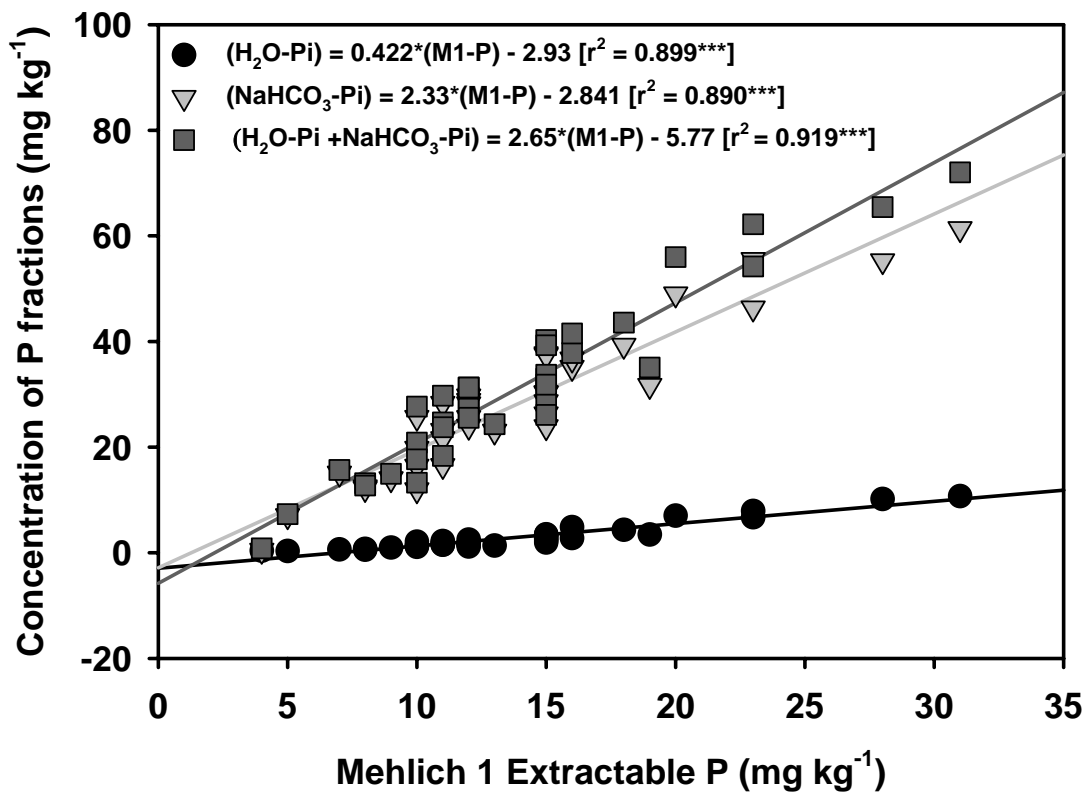
Fig. 3.2: The concentrations of deionized H_2O extractable Pi (H2O-Pi), 0.5 *M* NaHCO₃ extractable Pi (HCO₃-Pi), and H_2O-Pi plus HCO₃-Pi as a function of Mehlich 1 extractable P (M1-P) (*** p value <0.0005).

Table 3.1: Litter application rates and corresponding plant available N (PAN) and application rates for each treatment.

P Source	Application Strategy†	Rates applied in 2000			Rates applied in 2001-2003		
		Litter applied	PAN‡ applied as litter	P Applied	Litter applied	PAN‡ applied as litter	P Applied
		Mg ha^{-1}	---------kg ha^{-1}---------		Mg ha^{-1}	---------kg ha^{-1}---------	
Check	-----	0.0	0	0	0.0	0	0
Non-treated litter	NBNL	4.0	112	79	4.3	112	64
Triple superphosphate	NBNL	0.0	0	79	0.0	0	64
Alum treated litter	NBAL	3.4	112	54	3.9	112	56
Triple superphosphate	NBAL	0.0	0	54	0.0	0	56
Non-treated litter	CR	1.8	50	35	2.4	61	35
Alum treated litter	CR	2.2	72	35	2.5	70	35
Triple superphosphate	CR	0.0	0	35	0.0	0	35
Non-treated litter	2CR§	3.6	100	70	4.7	123	70
Alum treated litter	2CR§	4.4	144	70	4.9	140	70
Triple superphosphate	2CR§	0.0	0	70	0.0	0	70
Non-treated litter	STP	2.2	63	44	3.1	81	46

†NBNL, P rate supplied by the N-based non-treated poultry litter application of 112 kg PAN ha^{-1}; NBAL, P rate supplied by the N-based alum-treated poultry litter application of 112 kg PAN ha^{-1}; CR, P application rate of 35 kg P ha^{-1}, equivalent to estimated crop P removal; and 2CR, P Phosphorus application rate of 70 kg P ha^{-1}, equivalent to estimated 2-years of crop P removal, applied prior to planting in 2000 and 2002; STP, soil test recommended P application rate.

‡PAN was estimated to equal 60% of organic N plus 50% of NH$_4$-N applied in poultry littler.

§2CR treatments received P applications only in the 2000 and 2002 growing seasons and only NH$_3$NO$_3$-N in 2001 and 2002.

Table 3.2: Elemental composition of the alum-treated
poultry litter (ATPL) and non-treated poultry litter (NPL)
used in 2000 and that used in 2001-2003 corrected to a dry weight.

Element	2000		2001-2003	
	NPL	ATPL	NPL	ATPL
	--------------- mg kg^{-1} ---------------			
NH$_4$-N	11015	16486	5756	8171
Total-N	48311	57562	44379	48939
P	19587	15982	14861	14244
K	30565	30744	35590	33878
Ca	17997	15192	21994	23724
Mg	8120	10397	8585	8473
S	7139	31486	7837	17368
Zn	559	596	645	663
Cu	811	884	969	1039
Mn	668	712	747	2411
Na	10006	9126	8793	8286
Al	1221	8563	754	6648
Moisture %	26.6	27.0	28.2	23.4
Al/P ratio	0.06	0.54	0.05	0.47

Table 3.3: Forage yield and P removed in forage.

P Source	Application Strategy†	----2000----		----2001----		----2002----		----2003----	
		Yield	P	Yield	P	Yield	P	Yield	P
		---------------------------------kg ha^{-1}---------------------------------							
Check	-----	5583	12.5	4349	10.1	5746	9.9	7347	15.9
Non-treated litter	NBNL	4255	13.5	4394	14.9	5802	15.9	9236	32.2
Triple superphosphate	NBNL	5652	14.3	5368	16.1	6901	16.4	9039	28.6
Alum treated litter	NBAL	4150	10.9	4941	14.9	5958	14.8	8416	26.5
Triple superphosphate	NBAL	5755	15.2	4868	14.5	6147	15.6	8255	26.0
Non-treated litter	CR	4787	12.3	4614	13.7	6573	15.9	9432	31.2
Alum treated litter	CR	4887	13.1	4849	13.7	6620	15.5	8348	24.1
Triple superphosphate	CR	5670	13.3	5088	14.2	5995	14.2	9176	26.6
Non-treated litter	2CR§	3863	12.1	5144	14.4	5459	13.2	8446	23.8
Alum treated litter	2CR§	4921	13.2	5622	14.1	6312	15.5	8660	24.1
Triple superphosphate	2CR§	6053	15.5	5235	13.5	6172	15.3	8075	22.5
Non-treated litter	STP	4741	13.1	3943	12.7	5532	14.5	8174	27.4
	LSD (p<0.05)=	757	2.2	NS	NS	NS	NS	NS	5.2

†NBNL, P rate supplied by the N-based non-treated poultry litter application of 112 kg PAN ha^{-1}; NBAL, P rate supplied by the N-based alum-treated poultry litter application of 112 kg PAN ha^{-1}; CR, P application rate of 35 kg P ha^{-1}, equivalent to estimated crop P removal; and 2CR, P Phosphorus application rate of 70 kg P ha^{-1}, equivalent to estimated 2-years of crop P removal, applied prior to planting in 2000 and 2002; STP, soil test recommended P application rate.
§2CR treatments received P applications only in the 2000 and 2002 growing seasons and only NH_3NO_3-N in 2001 and 2002.

Table 3.4: The total crop P removal, P applied and net P applied during the 4-year study, and the resulting Mehlich 1 extractable P (M1-P), and ammonium oxalate extractable Al, Fe, P found in soils collected in the spring of 2004.

P Source‡	Application Strategy†	Crop P Removal	Total P applied	Net P applied	M-1 P	Ammonium Oxalate extractable		
						Al	Fe	P
		------------kg P ha^{-1}-----------			--------------mg kg^{-1}---------------			
Check	-----	48	0	-48	5.3	1726	1784	175
NPL	NBNL	77	257	181	18.0	1708	1773	259
TSP	NBNL	76	257	182	23.7	1813	1785	286
ATPL	NBAL	67	212	145	16.3	1770	1717	269
TSP	NBAL	71	212	141	21.3	1880	1878	288
NPL	CR	73	141	68	11.0	1827	1876	223
ATPL	CR	66	141	75	12.0	1966	1939	253
TSP	CR	68	141	73	11.7	1755	1758	225
NPL	2CR§	64	141	77	11.0	1839	1875	212
ATPL	2CR§	67	141	74	11.0	1764	1720	243
TSP	2CR§	67	141	74	10.3	1825	1809	222
NPL	STP	68	181	114	14.0	1623	1646	228
Analysis of variance and results from contrast comparisons								
Source		NS	---	---	NS	NS	NS	***
Rate		NS	---	---	***	NS	NS	***
Source*Rate		NS	---	---	NS	NS	NS	NS
NPL vs. TSP		NS	---	---	NS	NS	NS	NS
ATPL vs. TSP		NS	---	---	NS	NS	NS	NS
NPL vs. ATPL		NS	---	---	NS	NS	NS	*
NBNL vs. NBAL		NS	---	---	NS	NS	NS	NS
NBNL vs. CR		NS	---	---	***	NS	NS	**
NBNL vs. 2CR		NS	---	---	***	NS	NS	***
NBAL vs. CR		NS	---	---	***	NS	NS	**
NBAL vs. 2CR		NS	---	---	***	NS	NS	**
CR vs. 2CR		NS	---	---	NS	NS	NS	NS

†NBNL, P rate supplied by the N-based non-treated poultry litter application of 112 kg PAN ha^{-1}; NBAL, P rate supplied by the N-based alum-treated poultry litter application of 112 kg PAN ha^{-1}; CR, P application rate of 35 kg P ha^{-1}, equivalent to estimated crop P removal; and 2CR, P Phosphorus application rate of 70 kg P ha^{-1}, equivalent to estimated 2-years of crop P removal, applied prior to planting in 2000 and 2002; STP, soil test recommended P application rate.
‡NPL, Non-treated poultry litter; TSP, triple superphosphate fertilizer; ATPL, alum-treated poultry litter.
§2CR treatments received P applications only in the 2000 and 2002 growing seasons and only NH_3NO_3-N in 2001 and 2002.
NS, Non-significant at 0.05 probability level
* Significant at the 0.01 probability level.
*** Significant at the 0.0001 probability level.

Table 3.5: The inorganic (Pi), and organic (Po) P extracted using dionized H_2O, 0.5 M $NaHCO_3$, and 0.1 M NaOH during the fractionation of soils collected in the spring of 2004.

P source‡	Rate†	H_2O	$NaHCO_3$	NaOH	H_2O	$NaHCO_3$	NaOH
			Pi			Po	
		---------------------------------mg kg^{-1}----------------------------					
Check	-----	0.4	8	155	12	26	165
NPL	NBNL	5.3	37	204	13	23	157
TSP	NBNL	8.0	53	243	11	19	162
ATPL	NBAL	2.8	31	201	13	24	198
TSP	NBAL	5.6	46	212	13	23	163
NPL	CR	1.5	21	173	13	22	172
ATPL	CR	1.8	24	188	13	25	189
TSP	CR	2.1	24	166	11	23	159
NPL	2CR	1.7	21	191	14	25	167
ATPL	2CR	1.4	21	177	11	25	196
TSP	2CR	1.3	22	171	11	25	173
NPL	STP	2.8	27	176	10	21	165
LSD (p<0.05)=		2.5	6	37	NS	NS	24

†NBNL, P rate supplied by the N-based non-treated poultry litter application of 112 kg PAN ha^{-1}; NBAL, P rate supplied by the N-based alum-treated poultry litter application of 112 kg PAN ha^{-1}; CR, P application rate of 35 kg P ha^{-1}, equivalent to estimated crop P removal; and 2CR, P Phosphorus application rate of 70 kg P ha^{-1}, equivalent to estimated 2-years of crop P removal, applied prior to planting in 2000 and 2002; STP, soil test recommended P application rate.
‡NPL, Non-treated poultry litter; TSP, triple superphosphate fertilizer; ATPL, alum-treated poultry litter.
NS, Non-significant at 0.05 probability level

Chapter 4: Impact of Alum-Treated Poultry litter Applications on Soil Chemical Properties: Soil pH, Exchangeable Al, and H_2O extractable P

Abstract

The treatment of poultry (*Gallus gallus domesticus*) litter with alum is a management strategy with excellent potential to reduce P availability to surface water runoff upon application to agricultural lands. However, limited research has been conducted to evaluate the possible negative impacts this practice may have on soil pH and exchangeable Al content of soils receiving alum-treated poultry litter (ATPL). Also, only limited data are available evaluating the impact of soil type on its effectiveness in minimizing water extractable soil P (H_2O-P). Therefore, a laboratory incubation study was utilized to evaluate the effects of ATPL applications on H_2O-P, soil pH and exchangeable Al in soils with pH values ranging from near neutral to acidic. Three poultry litter sources, one which had received no alum additions and two that had received alum additions were utilized in the study. These litter sources and an inorganic P source were applied at P-based rates ranging from 65 to 262 mg P kg^{-1}. Soils representing three soil series were included. Results of this incubation demonstrated that litter applications can significantly increase soil pH after 1-month of incubation. However, these increases were followed by subsequent decreases in soil pH to levels generally below or equal to that found in the untreated check treatments. The applied amounts of total N, NH_4-N and calcium carbonate equivalent more readily explained differences in soil pH resulting from litter applications than did the amounts of Al and S applied in the litter sources. Also, ATPL application did not significantly change the relationship between soil pH and exchangeable Al concentrations in treated soils. Application of ATPL resulted in reduced H_2O-P compared to NPL and KH_2PO_4 regardless of soil type and pH. However, differences in the soluble P concentrations found between the two ATPL litter sources did not explain differences in the H_2O-P concentrations in the amended soils.

Abbreviations:

ATPL: Poultry litter treated with alum

A10: 0-P check treatments compared to treatments receiving litter which had received 0.09 kg alum bird^{-1}

A5: 0-P check treatments compared to treatments receiving litter which had received 0.05 kg alum bird^{-1}

A0: 0-P check treatments compared to treatments receiving litter which had received no alum additions

H_2O-P: Water extractable soil P

NPL: Normal poultry litter without alum additions

Introduction

The treatment of poultry (*Gallus gallus domesticus*) litter with alum ($Al_2(SO_4)_3 \bullet 16H_2O$) is gaining favor as a management strategy to reduce soluble P concentrations in litter (Moore et al., 2000).   Various studies have been conducted to evaluate the effectiveness of alum treatment in reducing P solubility in poultry litter. Moore and Miller (1994) conducted a laboratory incubation that showed that alum treatment of poultry litter at a rate of 200 g alum kg^{-1} reduced the concentration of H_2O extractable P in litter by approximately 75% after 1 wk of incubation. Miles et al. (2003) conducted pen trials in which alum was applied at a rate of 0.091 kg $bird^{-1}$ to pens containing broiler chickens receiving various diet formulations designed to alter the availability of P. They found that these alum applications reduced the soluble P concentrations in litters by 30 to 60% depending on dietary formulation. Sims and Luka-McCafferty (2002) confirmed the effectiveness of applying alum to litter by conducting a farm scale experiment in which 97 commercial poultry houses received alum at a rate of 0.09 kg alum $bird^{-1}$ and 97 houses received no alum applications. Data from this study showed that alum applications resulting in an average Al to P ratio of 0.57 resulted in a reduction in soluble P of approximately 70%.

These reductions in the solubility of P in ATPL have also been shown to result in decreased concentrations of extractable soil P after application compared to that found in soils receiving non-treated poultry litter (NPL). Initial laboratory incubation of soils treated with ATPL and NPL revealed that application of ATPL containing 100 g alum kg^{-1} resulted in approximately 50 to 65% lower H_2O extractable P compared to NPL treated soils seven days after application, depending on soil pH (Shreve et al., 1996). These decreased H_2O extractable P concentrations were maintained throughout the 294-d incubation. Staats et al. (2004) conducted 24-h and 25-d desorption studies and found that P desorption at 24 hr after application from soils receiving ATPL was reduced by 7 to 20% depending on soil type. At 25 d after application this reduction was approximately 13% for all soils. Data evaluating the long-term availability of P after application of ATPL to soils were presented by Warren et al. (2006). They found that N-based applications of ATPL to field corn (*Zea mays* L.) resulted in lower Mehlich 1 and H_2O extractable P compared to that found in treatments receiving equivalent N-based applications of NPL in the Coastal Plain and Piedmont regions of Virginia. In Coastal Plain soils, the reduced P status could be attributed not only to reduced P application rates, but also to decreased availability of the applied P. Moore et al. (1999) also presented soil data collected after three years of ATPL application to tall fescue (*Festuca arundinacea*), which showed lower concentrations of both Mehlich 3 and H_2O extractable P in soils receiving ATPL compared to those receiving NPL even when both were applied at similar P rates.

These reductions in the concentration of soluble P in ATPL and subsequent decreases in the P status of soils treated with ATPL have been shown to result in decreased P concentrations in surface runoff. Initial evaluation of the effects of alum addition to poultry litter on runoff P concentrations after litter applications revealed that applications of litter containing a 1:5 ratio of alum to litter resulted in as much as an 87% reduction in soluble P concentrations in runoff compared to treatments receiving NPL

(Shreve et al., 1995). Moore et al. (2000) also evaluated runoff P concentrations after the application of ATPL or NPL to small (0.405 ha) watersheds constructed in fescue pastures. They found that treatment of litter with alum at a rate of 0.09 kg bird^{-1} in commercial production houses reduced soluble P concentrations in runoff resulting from natural rainfall by an average of 73% during the 3-yr study period when both were applied at rates of 4460 kg litter ha^{-1} yr^{-1} during the first 2 yr and 7136 kg litter ha^{-1} yr^{-1} during the third year. Warren et al. (2006) also observed reduced concentrations of soluble P in runoff from small runoff plots established in conventionally tilled corn (*Zea mays* L.) receiving ATPL compared to treatments receiving NPL.

Despite this volume of research evaluating the effectiveness of alum in reducing P availability in poultry litter and litter amended soils, little data are available evaluating its effects on other soil chemical characteristics. Sims and Luka-McCafferty (2002) showed that ATPL contained elevated concentrations of both total and soluble Al compared to that found in NPL. The pH of ATPL was also reduced by an average of 0.6 pH units. Moore et al. (2000) also showed that alum additions reduced litter pH which in turn suppressed NH$_3$ volatilization in the production house. The elevated Al content and suppressed pH in poultry litter treated with alum raises concern that the application of ATPL may unfavorably alter the pH and soluble Al content of soils since Al has the potential to be phytotoxic (Sims and Luka-McCafferty, 2002). Moore et al. (1999) stated that applications of ATPL and NPL resulted in elevated soil pH compared to applications of NH$_4$NO$_3$ and that exchangeable Al was elevated only in plots receiving the inorganic N source. Warren et al. (2006) presented soil pH and exchangeable Al concentration data for soils receiving three annual applications of NPL, ATPL, or NH$_4$NO$_3$ as the N source for corn production.   Again, they found that applications of NH$_4$NO$_3$ as the N source resulted in suppressed soil pH and elevated exchangeable Al compared to both litter sources. However, in this experiment soil pH was significantly reduced in treatments receiving ATPL compared to that found in NPL treatments at one of the two field study locations.

Various studies have been conducted to evaluate the effects of animal waste application on the pH of acidic soils. The results of these studies vary depending on initial soil and manure characteristics but generally show that manure applications to acidic soils result in increased soil pH (Iyamuremye et al., 1996; Stuart and Fonteno, 1993; Wong et al., 1998; and Whalen et al., 2000). However, these studies were all relatively short-term evaluations of the effect of manure applications on soil pH. In fact, the duration of these incubation studies ranged from 14 to 91-d. Whalen et al. (2000) presented data showing that 60 days after application of beef manure, soil pH increased by 0.8 to 1.2 units depending on initial soil pH. Applications of composted poultry litter to a loamy sand soil with an initial pH of 4.2 also resulted in increased pH after 91 days of incubation (Stuart and Fonteno, 1993). Although these studies provide evidence of the initial increase in soil pH after application, they do not provide evidence of long-term adjustment of soil pH. Also, these studies do not provide insight into how manure applications may affect the pH of soils with near neutral pH values.

Therefore, the objectives of this study were to evaluate the effects of broiler litter application on the pH and exchangeable Al content of soils with initial pH values ranging from acidic to near neutral and to determine if the treatment of poultry litter with alum

impacted these parameters. The impact of soil pH on the efficiency with which ATPL reduces water extractable soil P (H_2O-P) was also evaluated. In addition, previous researchers have suggested that the relative P extractability of litter P may be a useful estimate of P source coefficients for use in P site index calculations used to assess risk of off-site P transport from agricultural fields (Leytem et al., 2004). The use of relative P availability instead of litter P solubility measurements may be favorable because it accounts for organic P release after incorporation. Therefore, data collected in this incubation were utilized to evaluate the impacts of soil type and soil pH on the relative H_2O extractability of litter-derived P.

Materials and Methods

Soils

Three soils were collected from agricultural fields in Virginia that had no recent history of animal manure application. These soils included a Davidson loam, Frederick silt loam, and Bojac sandy loam, which are representative soils from the Piedmont, Shenandoah Valley, and Coastal Plain regions of Virginia, respectively. Characteristics of these three soils are presented in Table 1. The soils collected from a 0 to 15 cm depth were air-dried and ground to pass a 2-mm sieve, mixed thoroughly and split into 3 containers. One container of each of the three soils was not subjected to any alterations until initiation of the incubation study. The two remaining containers of each soil were subjected to pH adjustment to 4.5 or 5.5. The pH adjustment was conducted by adding appropriate amounts of either H_2SO_4 or CaO, as determined by titration of a 1:10 soil to 0.01 M $CaCl_2$ mixture. The treated soils were then submitted to a series of wetting and drying cycles. These cycles consisted of moistening the soils to a moisture content equal to 60% of field capacity and mixing with a cement mixer. The soils were then spread on a table in a greenhouse and allowed to dry. After drying the soils were again ground and pH was measured. Each wetting and drying cycle was completed during a 4-d period and the pH was deemed stable after 3 cycles without a change in soil pH greater than $\pm$ 0.05 units.

P Sources

Two of the poultry litters used in this incubation were collected from poultry houses included in the study presented by Sims and Luka-McCafferty (2002). The alum-treated poultry litter collected from these houses (A10) received alum at an approximate rate of 0.09 kg bird[-1] prior to the introduction of each flock. The non-treated litter collected from these houses (A0) was collected from a house that had received no alum additions. An additional alum-treated poultry litter (A5) was collected from a poultry production house located in the Shenandoah Valley of Virginia, which had received alum at an approximate rate of 0.05 kg bird[-1] prior to the introduction of each flock. Selected chemical characteristics of each of these litters are presented in Table 2. The inorganic P source used in this incubation was KH_2PO_4. This was applied to soils as a solution containing 10.5 g P L^{-1}.

Soil and Poultry Litter Characterization

Bulk soils were analyzed for soil particle size determination using the hydrometer method (Gee and Bauder, 1986) and ammonium oxalate extractable P, Fe, and Al (Pote et al., 1999). Soil pH was determined on a 1:10, soil to 0.01 M CaCl$_2$ solution ratio (Thomas, 1996), exchangeable Al was determined using a 1:5 soil to 1 M KCl ratio (Bertsch and Bloom, 1996) and H$_2$O-P was determined using Molybdate blue analysis (Murphy and Riley, 1962) on 1:10 soil to deionized H$_2$O extracts (Kuo, 1996).

Total elemental analysis of each poultry litter was conducted by standard methods of the Agricultural Service Laboratory, Clemson University. Water soluble P concentrations in litters were determined using Molybdate blue analysis (Murphy and Riley, 1962) of 1:10 litter to deionized H$_2$O extracts (Leytem et al., 2004). Litter pH was determined using a 1:5 litter:deionized H$_2$O ratio. The calcium carbonate equivalent was determined by A & L Eastern Agricultural Laboratories, Richmond, VA using method AOAC 955.01.

Experimental Design

The experimental design was a randomized complete block with three replications. After pH adjustment, 200-g of each soil representing the three pH levels was placed in 351 round plastic containers with diameters of 9 cm and depth of 5 cm. The four P sources were applied to the nine soils at rates of 66, 131, and 197 mg P kg^{-1} soil. Because this incubation also served to evaluate the effects of ATPL applications on soil P availability, an application of each P source at a rate of 262 mg P kg^{-1} soil was applied to the three Davidson soils due to its high P sorption capacity. A 0-P check treatment was included for each of the nine soils. This treatment structure resulted in 129 treatments. After treatment application, soils were moistened to 60% of field capacity, lids with four 1-mm holes were placed on each container and the containers were placed in an incubator at 25 $^{\circ}$C.

The soils were incubated for 1-yr during which containers were weighed every 5 to 7 d to determine moisture content and samples were taken from each container at 1, 3, 6 and 12-months after initiation. Prior to sample collection containers were weighed and the soil was mixed thoroughly. Samples of appropriate weight for the determination of H$_2$O extractable P, pH, and exchangeable Al were collected from each container and refrigerated at 4 $^{\circ}$C until extractions could be conducted. The containers were weighed again after sample collection. This weight and that determined prior to each sampling was used to determine container weights required to maintain the moisture content at 60% of field capacity in the reduced weight of soil.

Statistical Analysis

Analysis of variance was performed using the SAS PROC GLM procedure (SAS Institute, 2001), and Fisher's protected LSD was used to separate treatment means. Regression analyses were conducted using the SAS PROC REG procedure.

Calculation of Relative P extractability

The following method used to calculate relative P extractability was adopted from Leytem et al. (2004). First, the extractability of P in soils receiving either litter P or inorganic P was calculated as:

$$\text{Extractability of P (\%)} = \frac{(H_2O\text{-}P_{LP/IP} - H_2O\text{-}P_{Check}, \text{mg P kg}^{-1}) \times 100}{(\text{Total P added})}$$

Where:

$H_2O\text{-}P_{LP/IP}$ = H_2O-P extracted from soils receiving litter P (LP) or inorganic P (IP);

$H2O\text{-}P_{check}$ = H_2O-P extracted from 0-P check soils.

The relative P extractability is then calculated as:

$$\text{Relative P extractability (\%)} = \frac{(\text{P extractability}_{LP}) \times 100}{(\text{P extractability}_{IP})}$$

Results and Discussion

pH Change through Time

The initial pH values for the 9 soils as measured prior to initiation of the incubations are presented in Table 3. As illustrated in Fig. 1 – 3 the pH adjustment was not maintained throughout the incubation. The pH of the 0-P check treatments changed considerably with time for each soil. Despite the difficulties in adjusting the pH of soils to specific values, the data collected proved valuable for assessing the differences in the effects of NPL and ATPL additions on soil pH.

Evaluation of general trends in soil pH resulting from the application of the four P sources is provided in Figs. 1 – 3. Application of the three broiler litter sources tended to increase soil pH relative to the 0-P check and KH_2PO_4 treatments at 1-month after initiation. In those soils for which the 0-P check treatment resulted in pH values above 5.5, the initial increase in pH was followed by a decrease in pH of litter treated soils at 3-months to values below that found in the 0-P check treatments. This decline in pH was less rapid in soils with 0-P check soil pH values below 5.5.

Data collected from this incubation study do not allow for an evaluation of the mechanisms by which litter applications changed soil pH with time or how these changes are related to initial soil pH. However, the variation in the response of soil pH over time among the different soils may have resulted from the impact of soil pH adjustment on microbial processes taking place in the soil. The rate of organic N mineralization decreases with decreasing pH, also, the oxidation of the resulting NH_4^+ to NO_3^- by Nitrosomonas and Nitrobacter is sensitive to decreased pH and can become negligible below pH values of 4.5 (Adams and Martin, 1984). Therefore, the prolonged elevation in soil pH for the Da2 and Fd2 soils receiving litter application could be a result of decreased rates of N transformation. Previous research has alluded to the effects of

microbial transformation on soil pH response to animal manure applications. Whalen et al. (2000) presented data showing that beef manure applications resulted in increased soil pH during an 8-wk incubation. Also, manure applications to soils in which net N mineralization and nitrification occurred resulted in slight decreases in soil pH after 8-wks of incubation compared to pH measurements taken directly after application. Data presented in Figs. 1 – 3 demonstrate that poultry litter can elevate the pH of soils initially, however given sufficient time the net result of litter applications will most often be a reduction in soil pH compared to application of inorganic P.

Effects of P Application Rate on pH

In an effort to more clearly quantify the effects of litter application on soil pH, linear regression was used to relate P application rate and soil pH for data collected at 1 and 12-months after initiation of the incubation. These sampling periods were chosen for analysis in order to evaluate the short-term and long-term effects of litter applications on soil pH. The results from this regression analysis are presented for each soil and P source in Table 4. Graphical examples of these analyses conducted for the three Frederick soils at 1 and 12-months, respectively are provided in Figs. 4 – 5. At 1-month, application of the three litter sources resulted in significant increases in soil pH with increasing P rate. However, at 12-months after application, soil pH decreased significantly with increasing litter application rate in soils with initial pH values above 5.5. Soil pH response to litter applications were less consistent in soils with pH values below 5.5, however, at these lower pH values, treatments resulted in either no significant response to application rate or a positive response to litter application. As previously mentioned the proton generating microbial activity was likely suppressed in these soils and therefore pH did not decrease with increasing application rate.

The slope and intercept estimates for the three litter sources presented in Table 4 were compared in order to evaluate differences in soil pH response to P application rate. These comparisons were made for each of the 9 soils. At 1-month these comparisons showed that the slopes resulting from A5 litter applications were often significantly greater than those resulting from A0 or A10 litter applications (Table 5). These differences were most prominent in the Bojac and Frederick soils because of their lower buffer capacities resulting from lower clay content (Table 1). The elevated pH in soils receiving A5 litter likely resulted from the elevated calcium carbonate equivalent supplied by this litter (Table 2). No significant differences were found in the response of soil pH to the application of A10 compared to A0 litter at 1-month after application (Table 5).

At 12-months after application, fewer significant differences were found when comparing the slopes resulting from regression of pH as a function of P application for the three litter sources (Table 5). Thus litter applications in this study generally resulted in similar pH values at 12-months regardless of litter characteristics. However, in the Bo2, Bo3 and Fd1 soils, slopes were significantly more negative for the A10 litter applications compared to the A0 litter applications. The trend for A10 litter applications to result in suppressed soil pH at 12-months is expected because the application of A10 litter resulted in greater total N applications compared to the A0 litter applications.

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Although the A10 litter received alum applications of 0.09 kg alum bird^{-1} and the A5 litter received 0.05 kg alum bird^{-1} when applied in the production houses, the final Al to P ratios were the same for each litter (Table 2). Therefore, the amount of Al applied in each of these two litter sources was similar. Also, the amounts of S applied in these two litter sources were similar, at 75 and 73 mg S kg^{-1} for the A10 and A5 litters, respectively, when applied at the 65 mg P kg^{-1} rate. These data suggest that mechanisms such as mineralization and nitrification have greater impacts on soil pH resulting from litter applications than treatment of litter with alum.

Soil pH and Exchangeable Al

For this analysis, linear regression models were constructed where the negative log of the molar concentration of exchangeable Al was plotted as a function of soil pH. Each linear regression model consists of data from treatments that differed only in the initial soil pH imposed on the treatment; each had received the same P rate and P source.

The results from the regression analyses generated from data collected at the 1 and 3-month sampling periods for the Davidson and Frederick soils are presented in Table 6. The Bojac soils were not included in this analysis because soil pH levels were such that exchangeable Al was limited to near detection limit concentrations, especially 1-month after litter application. These elevations in soil pH resulting from litter application also created difficulty in interpretation of results from the Frederick and Davidson soils. Graphical illustration of regression data for the 1-month sampling period for the Frederick soil is presented in Fig. 6. As soil pH increased in the Frederick soils above 5.8, the negative log of the exchangeable Al concentration plateaud (Fig. 6). This phenomenon occurred because the detection limit for the method used to determine exchangeable Al is equal to a negative log value of 5.7. Those litter sources that resulted in the greatest increase in soil pH at 1-month resulted in less positive slopes for regression models relating exchangeable Al and pH. For example the A5 litter resulted in the greatest increase in soil pH as a function of litter rate compared to the other two litter sources when applied to the three Frederick soils (Table 4). This resulted in less positive slopes (Table 6), in fact the 131 and 197 mg P kg^{-1} applications of A5 resulted in slopes not significantly greater than zero. Because of these effects, comparisons for the Frederick soil at 1-month cannot be used to accurately assess the effects of ATPL applications on the pH/exchangeable Al relationship. The significant differences between slope and intercept values resulting from P source applications to the Frederick soil compared to those resulting from the 0-P check treatments at 1-month (Table 7) can be attributed to the plateau effect.

The plateau effect also occurred for the Davidson soil at 1-month; but only at the 197 and 262 mg P kg^{-1} application rates where it caused significant differences in slope and intercept estimates when comparing the litter treatments to the KH$_2$PO$_4$ treatments (Table 7). Applications of the four P sources at 65 and 131 mg P kg^{-1} did not result in significantly different slope and intercept estimates compared to those found for the 0-P check treatments in the Davidson soil (Table 7). This provides evidence that ATPL applications do not adversely impact the relationship between exchangeable Al and soil pH, specifically at pH levels below which Al concentrations begin to elevate.

Because of the problems caused by elevated pH in litter-treated soils at 1-month, regression analysis, and slope and intercept comparisons were also conducted using data collected 3-months after initiation. This analysis showed no significant differences in the relationships between exchangeable Al and soil pH resulting from application of the four P sources compared to that found in the 0-P check treatments (Table 7). This shows that although treatment of poultry litter with alum may increase soluble Al content of litter (Sims and Luka-McCafferty, 2002), incorporation of this ATPL is likely not to result in a significant change in the relationship between exchangeable soil Al and soil pH.

Effects of P Application Rate on H$_2$O Extractable P

Data collected during this incubation allowed for the evaluation of H$_2$O-P in three different soils as a function of P rate, P source, soil pH, and time. The impact of P rate on H$_2$O-P concentrations in soils was determined using linear regression at 1 and 12-months. Graphical representation of these linear regression analyses are presented for the Frederick soils at 1 and 12-months in Figs. 7 – 8, respectively. The slope estimates from all linear regression analyses are presented in Tables 8 – 10. Regression statistics presented in Tables 8 – 10 show that P source application rate significantly affected H$_2$O-P concentrations in all soils except for Da2 at 1-month after application of the A10 litter and at 12-months after application of the A10 and A5 litters (Table 9). This lack of response results from not only the reduced P solubility in the A10 and A5 litters (Table 2) but also the elevated clay content and amorphous Fe and Al present in the Davidson soil (Table 1).

To determine the impact of both soil pH adjustment and P source on the efficiency with which P applications increased H$_2$O-P availability, slope comparisons were conducted. Both initial soil pH and P source significantly affected the efficiency with which P application increased H$_2$O-P (Tables 8 – 10). Within each soil, KH$_2$PO$_4$ was generally most efficient at increasing H$_2$O-P followed by A0, A5, and A10 in order of decreasing efficiency. The ATPL sources were effective in reducing P availability compared to NPL irregardless of soil pH. The decrease in P availability in soils treated with ATPL is in agreement with previous research (Moore et al, 1999; Staats et al., 2004; Shreve et al., 1996). However, the differences in efficiency with which the two ATPL sources increased H$_2$O-P are of interest. The A5 litter contained the same Al:P ratio and suppressed soluble P concentration compared to the A10 litter (Table 2), however, it was generally more efficient at increasing H$_2$O-P concentrations in soils. These differences were most prominent in the Bojac and Frederick soils at 1-month (Tables 8 and 10). It appears that the greater adsorption capacity of the Davidson soil prevented differences between the two ATPL sources from being significant (Table 9). These findings show that, although knowledge of the soluble P content of ATPL may be useful in determining the availability of litter P to runoff after surface applications (Delaune et al., 2004) these measurements may be of less value in determining P availability following incorporation.

Various studies have been conducted evaluating the impact of treating poultry litter with alum on soil P status (Shreve et al. 1996; Staats et al, 2004; Moore et al., 1999); however, none have compared ATPL collected from different production systems. Research has primarily focused on comparing ATPL to NPL collected from the same poultry production facility. Very little attention has been paid to the impact of variations

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in litter characteristics that may affect the efficiency with which alum additions impact long-term availability of litter P in soils.

Two possibilities may explain the increased efficiency with which the A5 litter increased H_2O-P. First, the A5 litter contained elevated calcium carbonate equivalent (Table 2) suggesting that it may have contained elevated amounts of Ca-bound phosphates which may dissolve upon pH reduction after application (Tasistro et al., 2004). Additionally the total P content of this litter was 30% less than that of the A10 litter. This likely resulted in an increase in the amount of organic compounds applied. Previous researchers have suggested that competitive adsorption of organic acids and anions may decrease the P adsorption capacity of soils (Hue, 1991). Mozaffari and Sims (1996) also noted the impact of organic compounds on P adsorption capacity of manured soils.

These results demonstrate that soluble P concentrations in ATPL should be used cautiously when estimating P availability after incorporation into soils. Continued understanding of how litter characteristics impact P availability in soils is needed in order to accurately estimate variations in P availability to off-site transport through surface runoff during periods between applications. This is particularly important in cultivated systems allowing for the incorporation of applied poultry litter.

Relative H_2O-P extractability

The relative H_2O-P extractability was determined for all soils and litter P sources applied at the 131 mg P kg^{-1} soil rate. The limited response of H_2O-P in the Davidson soils to P applications (Table 9) resulted in excessive variability in the calculated relative H_2O-P extractability in this soil. Therefore relative H_2O-P extractability values are presented only for the Bojac and Frederick soils (Table 11). Analysis of variance showed a three-way interaction between soil, source, and time. Therefore LSD values were calculated to compare each soil/litter combination at each sampling period and to determine how the relative H_2O-P extractability changed with time for each soil/litter combination.

Significant differences in relative P extractability between sampling periods were the result of fluctuations at 1 and 3-months (Table 11). Generally this was followed by no significant differences from 3 to 12-months. Recall, that soil pH also changed dramatically in these soils between the 1 and 3-month sampling periods (Figs. 1 and 3). This suggests that the soils are undergoing equilibration during this period, resulting in interactions between P release from litter sources and adsorption. This is consistent with findings of Crouse et al. (2002) who showed increased phosphodiesterase activity in litter-amended soils between weeks 1- 8 of a 20-week incubation study. Because of this variability at 1 and 3 months differences in the relative P extractability for a specific litter source as a function of soil type or soil pH is difficult.

Despite variation with time, the average relative P extractability calculated during the 12-mo incubation can be related to soil pH. Data presented in Fig. 9 shows that the relative P extractability for each litter source was negatively correlated with the soil pH at 12 months. These relationships were consistent across the two soil types evaluated. This consistency is likely a result of the similar clay and amorphous Al and Fe contents found

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in the Bojac and Frederick soils. This analysis shows that soil pH will be an important factor to consider when developing P source availability coefficients applicable to different soils.

These data show that short-term incubations such as that utilized by Leytem et al. (2004) may not be sufficient to assess the relative extractability of P using H_2O extractions. Leytem et al. (2004) also found considerable variation in H_2O-P relative extractability between 2 and 8-weeks of incubation of various organic P sources with an Evesboro loamy sand soil. Therefore, longer incubation periods may be useful in future efforts to develop P source availability coefficients.

Conclusions

Data presented show that the incorporation of broiler litter can increase soil pH shortly after application. However, this increase in soil pH is followed by a decline to a level equal to or below the initial pH value. Also, soil pH was significantly affected by litter source. However, elevated concentrations of Al and S in the two ATPL sources could not explain these differences. In fact, differences in soil pH response to the application of the three litter sources were better explained by the rates of calcium carbonate equivalent and total N supplied by the litter sources. It appears that although treatment of poultry litter may potentially affect these two characteristics which could in turn impact soil pH after application there is no direct impact of ATPL on soil pH.

The relationships between soil pH and exchangeable Al were not affected by the application of any of the P sources applied in this incubation study when evaluated at 1 and 3-months. This provides evidence that, although treatment of poultry litter can increase soluble Al concentrations found in litter (Sims and Luka-McCafferty, 2002), it does not affect the relationship between soil pH and exchangeable Al after application to soils. Therefore, production and environmental concerns associated with Al toxicity may be elevated by proper pH management through periodic soil testing and lime applications.

The ATPL sources were less effective at increasing H_2O-P concentrations in treated soils at all levels of pH adjustment. This is in agreement with findings of previous research. Of the two ATPL sources, the A5 litter that had received alum at a reduced rate was most efficient at increasing H_2O-P in soils. This was accomplished despite the reduced concentration of water soluble P in this litter compared to that found in the A10 litter. These findings suggest other ATPL characteristics also control the availability of P in these sources, particularly after incorporation into soils. Although the soluble P content of poultry litter may be a useful measure of risk to runoff P transport when surface applied, caution should be used when using this litter characteristic to assess the long-term availability in soils after incorporation.

Determination of relative P availability after incorporation of litter shows promise as a tool by which P source coefficients may be determined for P site index management tools. However, variations in soil characteristics such as soil pH can have profound impacts on this value. The data presented suggest that determination of relative P availability in combination with soil pH may be useful in estimating the long-term availability of P derived from poultry litter.

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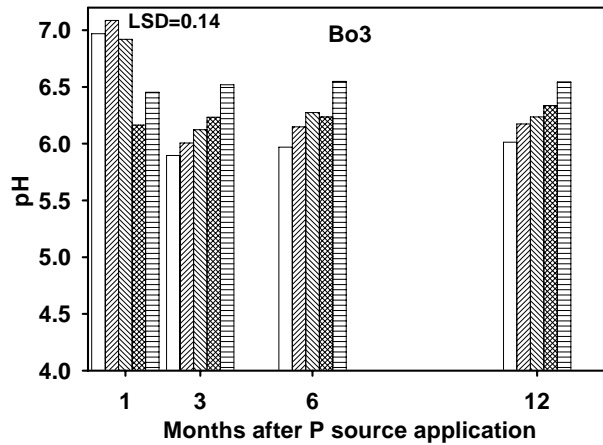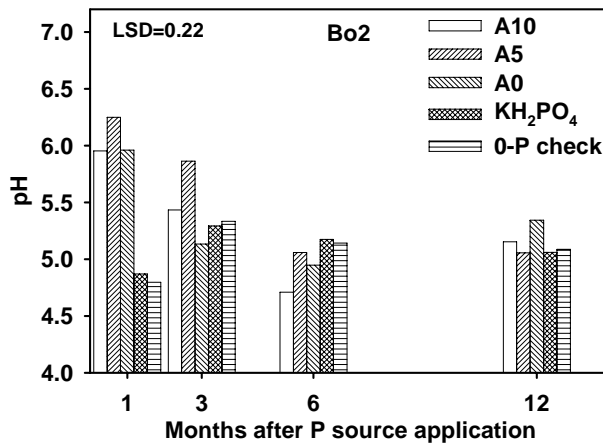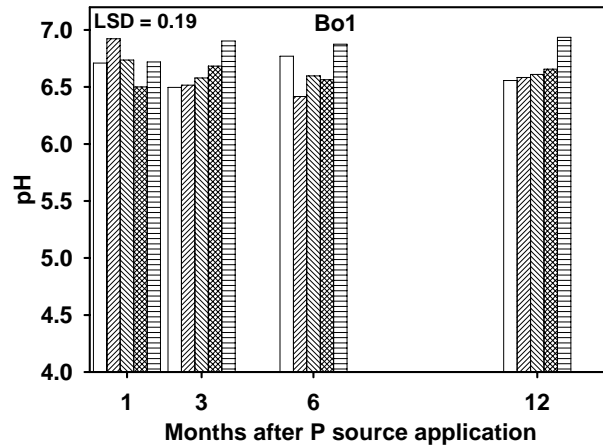
Fig. 4.1: Soil pH measured at each sampling period in the Bojac soil which had no pH adjustment prior to incubation (Bo1), the Bojac soil which was adjusted to a target pH of 4.5 (Bo2), and the Bojac soil which was adjusted to a target pH of 5.5 (Bo3) resulting from the 0-P check treatment, and treatments receiving A10 litter which had been treated with 0.09 kg alum bird[-1], A5 litter which had been treated with 0.05 kg alum bird[-1], A0 litter which had no alum additions, and KH_2PO_4 applied at 131 mg P kg^{-1}.

Fig. 4.2: Soil pH measured at each sampling period in the Davidson soil which had no pH adjustment prior to incubation (Da1), the Davidson soil which was adjusted to a target pH of 4.5 (Da2), and the Davidson soil which was adjusted to a target pH of 5.5 (Da3) resulting from the 0-P check treatment, and treatments receiving A10 litter which had been treated with 0.09 kg alum bird[-1], A5 litter which had been treated with 0.05 kg alum bird[-1], A0 litter which had no alum additions, and KH_2PO_4 applied at 131 mg P kg^{-1}.
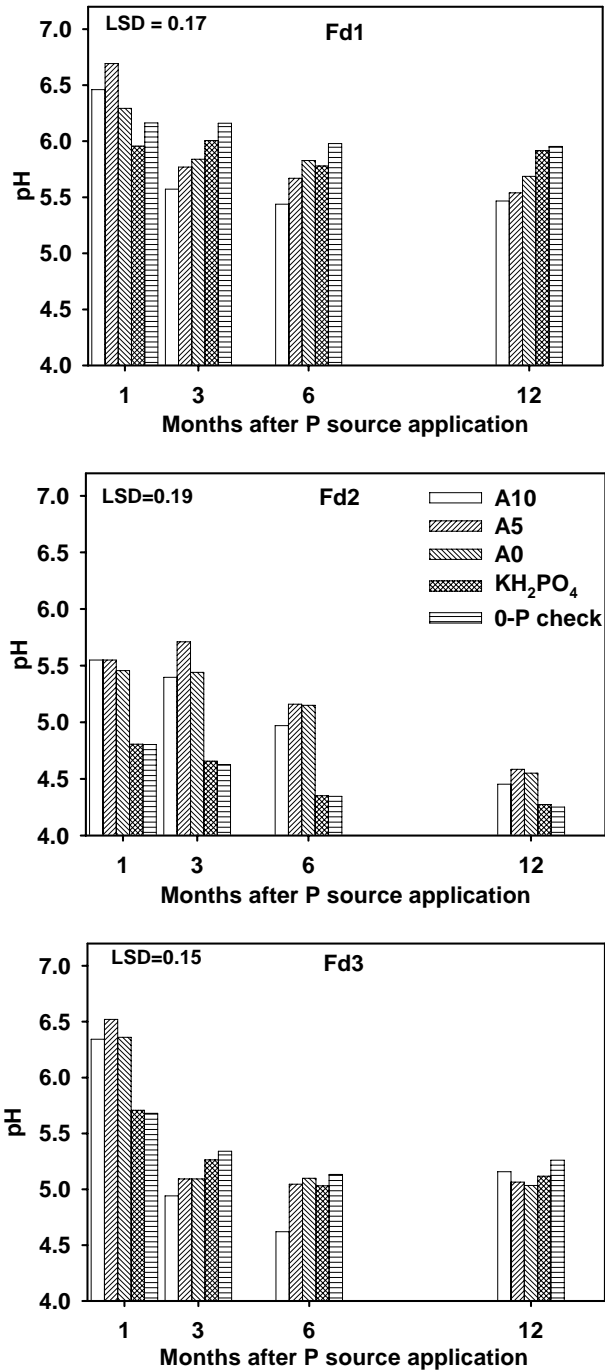
Fig. 4.3: Soil pH measured at 1, 3, 6, and 12-months in the Frederick soil which had no pH adjustment prior to incubation (Fd1), the Frederick soil which was adjusted to a target pH of 4.5 (Fd2), and the Frederick soil which was adjusted to a target pH of 5.5 (Fd3) resulting from the 0-P check treatment, and treatments receiving A10 litter which had been treated with 0.09 kg alum bird[-1], A5 litter which had been treated with 0.05 kg alum bird[-1], A0 litter which had no alum additions, and KH_2PO_4 applied at 131 mg P kg^{-1}.
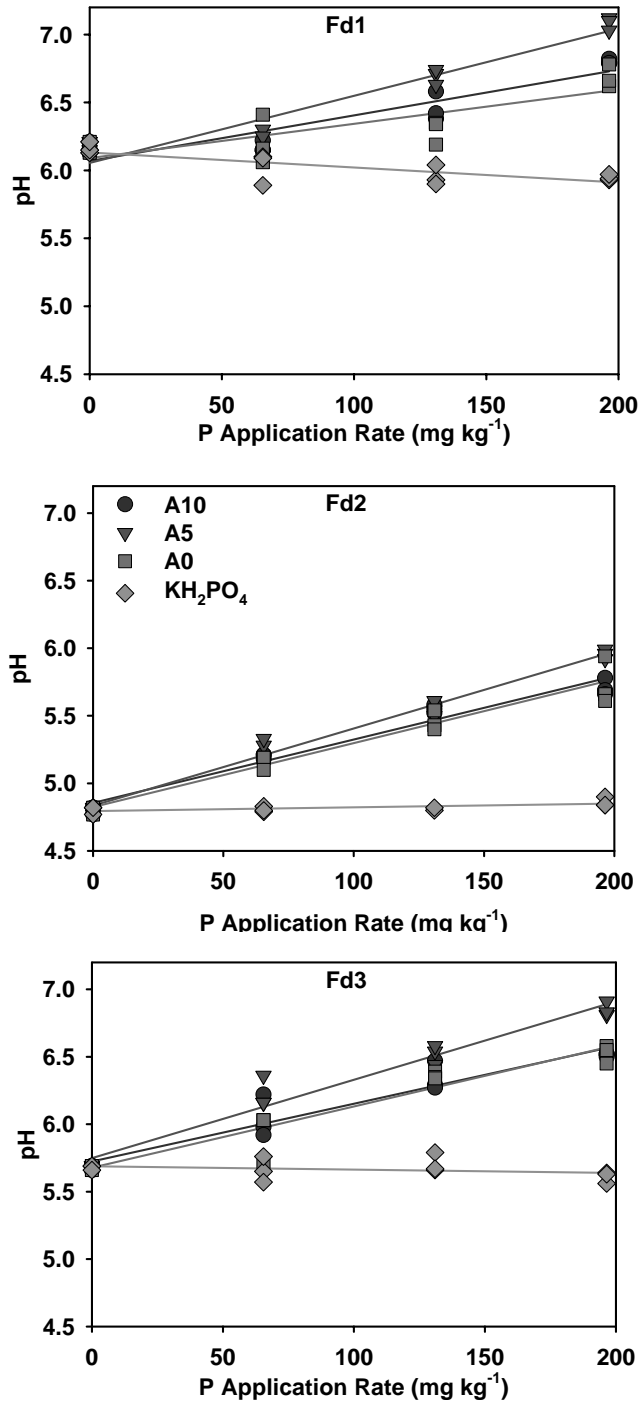
Fig. 4.4: Relationship between soil pH and P application rate 1-month after application of A10 litter which had been treated with 0.09 kg alum bird[-1], A5 litter which had been treated with 0.05 kg alum bird[-1], A0 litter which had no alum additions and KH_2PO_4 to the Frederick soil which had no pH adjustment prior to incubation (Fd1), the Frederick soil which was adjusted to a target pH of 4.5 (Fd2), and the Frederick soil which was adjusted to a target pH of 5.5 (Fd3) (Regression parameters and statistics are presented in Table 4).
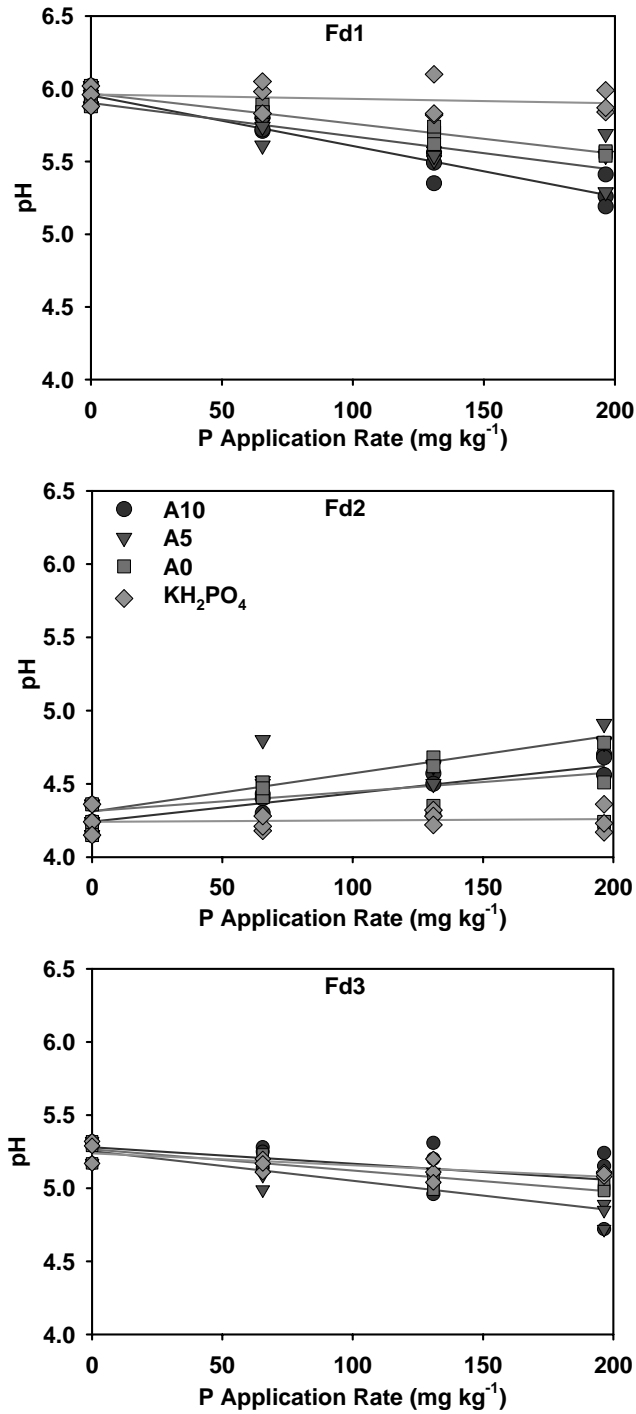
Fig 4.5: Relationship between soil pH and P application rate 12-months after application of A10 litter which had been treated with 0.09 kg alum bird[-1], A5 litter which had been treated with 0.05 kg alum bird[-1], A0 litter which had no alum additions and KH2PO4 to the Frederick soil which had no pH adjustment prior to incubation (Fd1), the Frederick soil which was adjusted to a target pH of 4.5 (Fd2), and the Frederick soil which was adjusted to a target pH of 5.5 (Fd3) (Regression parameters and statistics are presented in Table 4).
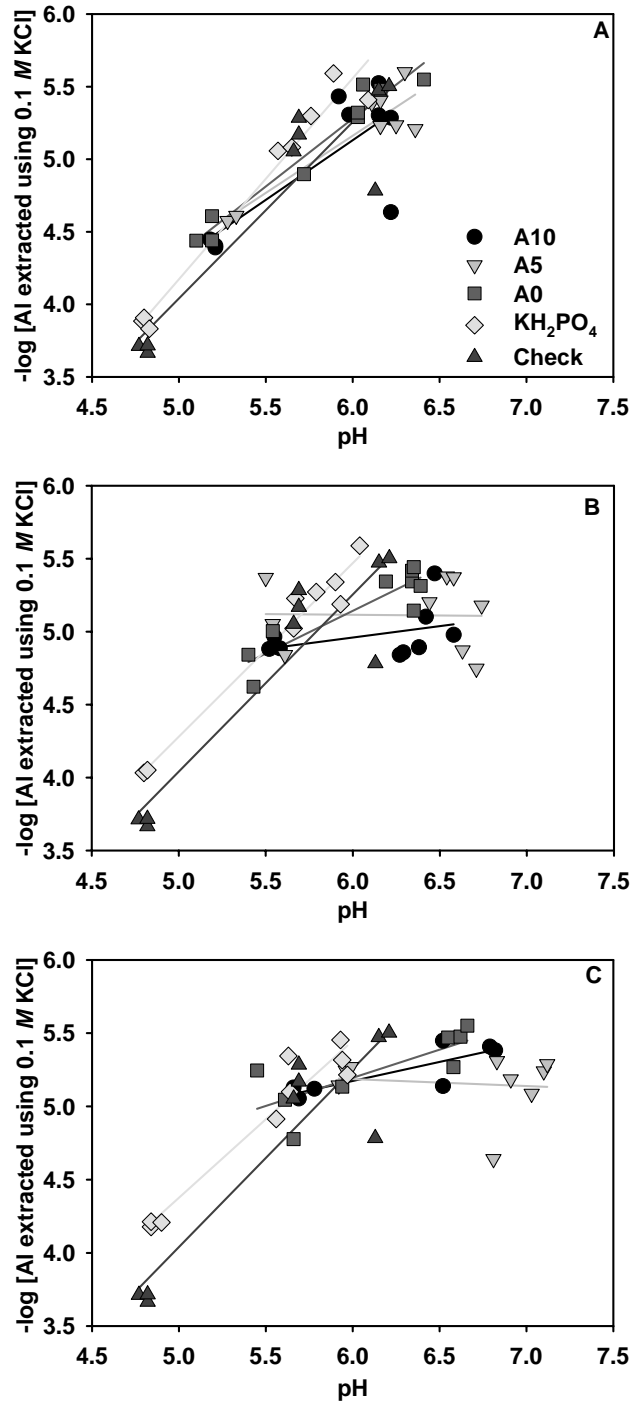
Fig. 4.6: Relationship between exchangeable soil Al and pH in the Frederick soils at 1-month in the 0-P check treatment and treatments receiving A10 litter which had been treated with 0.09 kg alum bird[-1], A5 litter which had been treated with 0.05 kg alum bird[-1], A0 litter which had no alum additions and KH2PO4 at rates of (A) 65, (B) 131, and (C) 197 mg P kg^{-1} of soil (Regression parameters and statistics are presented in Table 6).
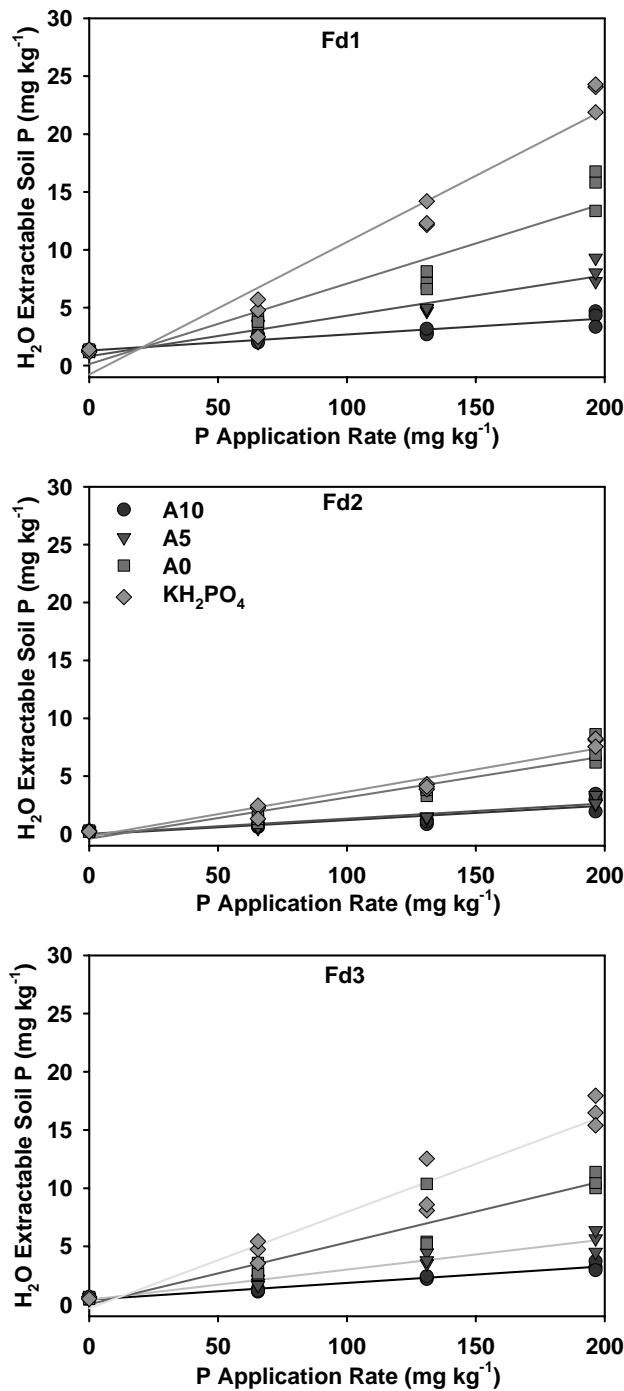
Fig. 4.7: Relationship between H_2O extractable P and P application rate 1-month after application of A10 litter which had been treated with 0.09 kg alum bird[-1], A5 litter which had been treated with 0.05 kg alum bird[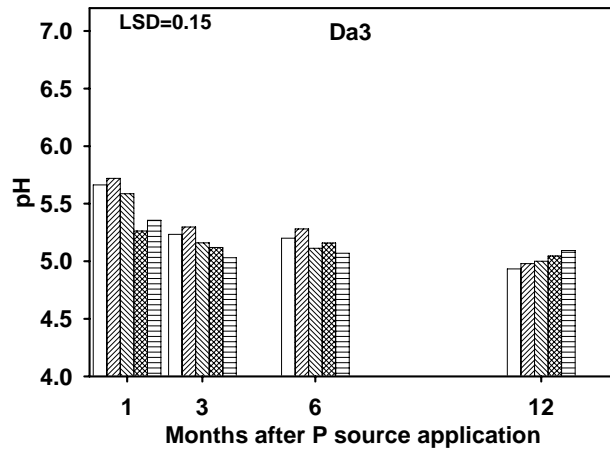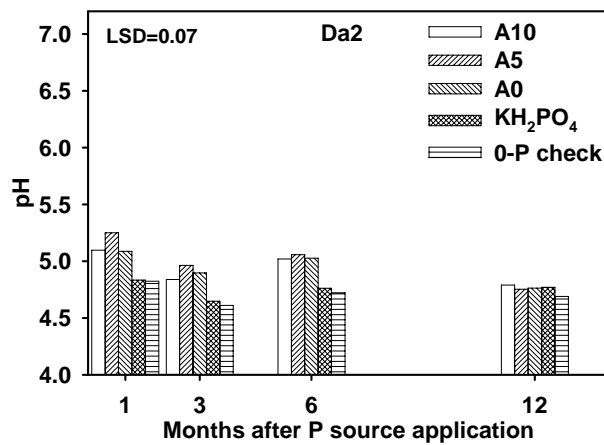-1], A0 litter which had no alum additions, and KH_2PO_4 to the Frederick soil which had no pH adjustment prior to incubation (Fd1), the Frederick soil which was adjusted to a target pH of 4.5 (Fd2), and the Frederick soil which was adjusted to a target pH of 5.5 (Fd3) (Regression line slope and statistics are presented in Table 10).

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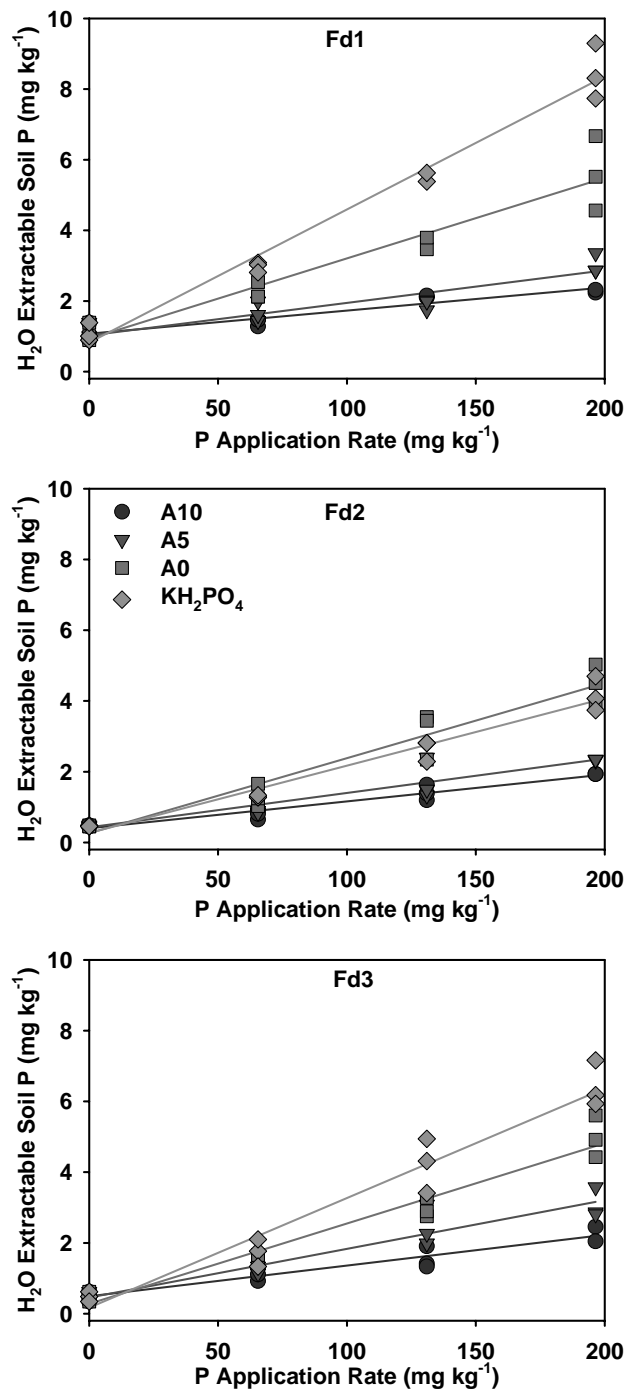
Fig 4.8: Relationship between H_2O extractable P and P application rate 12-months after application of A10 litter which had been treated with 0.09 kg alum bird[-1], A5 litter which had been treated with 0.05 kg alum bird[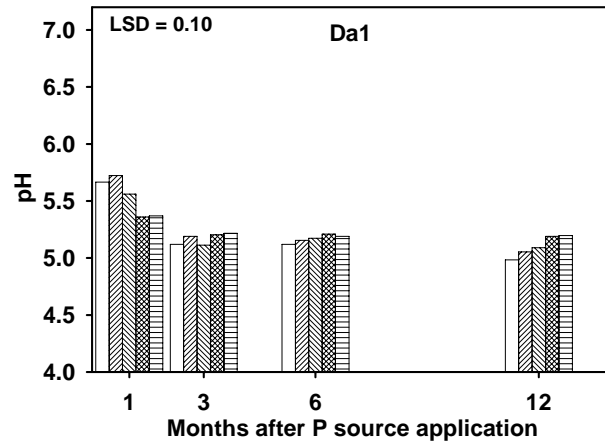-1], A0 litter which had no alum additions, and KH_2PO_4 to the Frederick soil which had no pH adjustment prior to incubation (Fd1), the Frederick soil which was adjusted to a target pH of 4.5 (Fd2), and the Frederick soil which was adjusted to a target pH of 5.5 (Fd3) (Regression line slope and statistics are presented in Table 10).

Fig 4.9: The relationship between relative H_2O extractability averaged across sampling periods and soil pH measured at 12 months in soils receiving A10 litter which had been treated with 0.09 kg alum bird[-1], A5 litter which had been treated with 0.05 kg alum bird[-1], A0 litter which had no alum additions. (* significant at the 0.05 probability level)

Table 4.1: Soil classification, textural analysis, pH and ammonium oxalate (AMOX) extractable Al and Fe of soils collected for this incubation study.

Soil	Soil Classification	Clay	Silt	Sand	pH	AMOX-Al	AMOX-Fe
		----------%-----------				--------mg kg^{-1}-------	
Bojac	coarse-loamy, mixed, semiactive, thermic Typic Hapludult	11	29	61	6.3	781	981
Davidson	fine, kaolinitic, thermic Rhodic Kandiudult	42	50	8	5.3	2777	2115
Frederick	fine, mixed, semiactive, mesic Typic Paleudult	10	57	33	6.3	764	615

Table 4.2: Selected chemical characteristics of the A10 litter that had received 0.09 kg alum bird^{-1}, A5 litter that had received 0.05 kg alum bird^{-1}, and A0 litter that had received no alum additions.

Element	A10	A5	NPL
	------------------------- mg kg^{-1} ---------------------		
NH4-N	25415	9172	11333
Total-N	67004	50898	47572
P	20116	14103	23096
Soluble P	346	202	3801
K	31889	35525	37195
Ca	27004	24157	28543
Mg	6354	7493	6996
S	23105	15760	7136
Zn	603	607	589
Cu	870	959	898
Mn	734	748	721
Na	9433	7768	10103
Al	8800	6174	1429
Al/P	0.44	0.44	0.06
pH	7.96	8.14	8.28
CCE	570	1401	Below Detection
Moisture	30.8	22.6	28.5

Table 4.3: The target pH and initial pH measured prior to initiation of the incubation study.

Soil Series	Soil ID	Target pH	Measured Initial pH
	Bo1	Natural	6.3
Bojac	Bo2	4.5	4.6
	Bo3	5.5	5.6
	Da1	Natural	5.3
Davidson	Da2	4.5	4.7
	Da3	5.5	5.6
	Fd1	Natural	6.3
Frederick	Fd2	4.5	4.9
	Fd3	5.5	5.7

Table 4.4: Linear regression parameters and statistics for soil pH measured at 1 and 12-months after initiation of the incubation study as a function of P application rate for each soil and P source combination.

Soil ID†	P Source‡	1 Month			12 Months		
		Slope	Intercept	R^2‡	Slope	Intercept	R^2‡
Bo1	A10	0.0021	6.5	0.371*	-0.0022	6.9	0.797*
Bo1	A5	0.0032	6.5	0.571*	-0.0025	6.9	0.878*
Bo1	A0	0.0022	6.5	0.338*	-0.0021	6.9	0.809*
Bo1	KH_2PO_4	-0.0021	6.7	0.748*	-0.0018	6.9	0.798*
Bo2	A10	0.0074	5.0	0.930*	-0.0020	5.2	0.306
Bo2	A5	0.0092	5.0	0.943*	0.0011	5.1	0.334*
Bo2	A0	0.0070	4.9	0.925*	0.0014	5.1	0.541*
Bo2	KH_2PO_4	0.0006	4.8	0.517*	-0.0005	5.1	0.417*
Bo3	A10	0.0033	6.5	0.874*	-0.0036	6.5	0.975*
Bo3	A5	0.0045	6.4	0.950*	-0.0030	6.6	0.868*
Bo3	A0	0.0034	6.4	0.895*	-0.0023	6.6	0.902*
Bo3	KH_2PO_4	-0.0016	6.4	0.536*	-0.0016	6.5	0.877*
Da1	A10	0.0020	5.4	0.817*	-0.0002	5.1	0.045
Da1	A5	0.0028	5.3	0.922*	-0.0006	5.2	0.599*
Da1	A0	0.0026	5.3	0.869*	-0.0001	5.2	0.029
Da1	KH_2PO_4	0.0000	5.3	0.003	0.0000	5.2	0.001
Da2	A10	0.0019	4.8	0.969*	0.0004	4.7	0.237
Da2	A5	0.0031	4.8	0.798*	0.0004	4.7	0.243
Da2	A0	0.0021	4.8	0.985*	0.0002	4.7	0.094
Da2	KH_2PO_4	0.0002	4.8	0.538*	0.0004	4.7	0.571*
Da3	A10	0.0021	5.4	0.941*	-0.0004	5.0	0.283*
Da3	A5	0.0024	5.5	0.377*	-0.0003	5.0	0.134
Da3	A0	0.0021	5.4	0.829*	-0.0002	5.0	0.063
Da3	KH_2PO_4	0.0002	5.3	0.038	-0.0003	5.1	0.206
Fd1	A10	0.0034	6.1	0.859*	-0.0035	6.0	0.920*
Fd1	A5	0.0049	6.1	0.910*	-0.0023	5.9	0.705*
Fd1	A0	0.0025	6.1	0.672*	-0.0021	6.0	0.926*
Fd1	KH_2PO_4	-0.0011	6.1	0.584*	-0.0003	6.0	0.055
Fd2	A10	0.0047	4.9	0.961*	0.0019	4.2	0.722*
Fd2	A5	0.0057	4.8	0.983*	0.0026	4.3	0.718*
Fd2	A0	0.0047	4.8	0.944*	0.0013	4.3	0.285
Fd2	KH_2PO_4	0.0003	4.8	0.416*	0.0001	4.2	0.010
Fd3	A10	0.0043	5.7	0.919*	-0.0011	5.3	0.248
Fd3	A5	0.0058	5.7	0.960*	-0.0020	5.3	0.785*
Fd3	A0	0.0045	5.7	0.922*	-0.0014	5.3	0.818*
Fd3	KH_2PO_4	-0.0002	5.7	0.083	-0.0008	5.2	0.549*

†Bo1, Bojac soil with no pH adjustment; Bo2, Bojac soil with target pH of 4.5; Bo3, Bojac soil with target pH of 5.5; Da1, Davidson soil with no pH adjustment; Da2, Davidson soil adjusted with pH of 4.5; Da3, Davidson soil with target pH of 5.5; Fd1, Frederick soil with no pH adjustment; Fd2; Frederick soil with target pH of 4.5; Fd3, Frederick soil with target pH of 5.5.
‡ A10, litter which had received 0.09 kg alum bird[-1]; A5, litter which had received 0.05 kg alum bird[-1]; A0, litter which had received no alum additions.
‡R^2 values followed by * are significant at the p<0.01 level.

Table 4.5: P values used to determine differences in the relationships between soil pH and P application rate resulting from A10, A5 and A0 litter sources at 1 and 12-months after initiation of the incubation study.

Soil ID†	Comparison‡	1 Month	12 Months
		--- P value for Slope Comparisons ---	
Bo1	A10 vs. A0	0.9298	0.8096
Bo1	A5 vs. A0	0.4613	0.3799
Bo1	A10 vs. A5	0.3806	0.5572
Bo2	A10 vs. A0	0.6725	0.0040
Bo2	A5 vs. A0	0.0340	0.6678
Bo2	A10 vs. A5	0.0788	0.0091
Bo3	A10 vs. A0	0.8730	0.0002
Bo3	A5 vs. A0	0.0298	0.1004
Bo3	A10 vs. A5	0.0258	0.1654
Da1	A10 vs. A0	0.1362	0.8481
Da1	A5 vs. A0	0.6330	0.0840
Da1	A10 vs. A5	0.0326	0.1840
Da2	A10 vs. A0	0.2605	0.4948
Da2	A5 vs. A0	0.0273	0.4998
Da2	A10 vs. A5	0.0146	0.9856
Da3	A10 vs. A0	0.9865	0.5608
Da3	A5 vs. A0	0.7290	0.7895
Da3	A10 vs. A5	0.7252	0.7581
Fd1	A10 vs. A0	0.2523	0.0013
Fd1	A5 vs. A0	0.0040	0.6627
Fd1	A10 vs. A5	0.0248	0.0528
Fd2	A10 vs. A0	0.9320	0.4337
Fd2	A5 vs. A0	0.0423	0.1428
Fd2	A10 vs. A5	0.0178	0.3074
Fd3	A10 vs. A0	0.6578	0.6305
Fd3	A5 vs. A0	0.0350	0.1583
Fd3	A10 vs. A5	0.0116	0.2136

†Bo1, Bojac soil with no pH adjustment; Bo2, Bojac soil with target pH of 4.5; Bo3, Bojac soil with target pH of 5.5; Da1, Davidson soil with no pH adjustment; Da2, Davidson soil adjusted with pH of 4.5; Da3, Davidson soil with target pH of 5.5; Fd1, Frederick soil with no pH adjustment; Fd2; Frederick soil with target pH of 4.5; Fd3, Frederick soil with target pH of 5.5.

‡ A10, litter which had received 0.09 kg alum bird^{-1}; A5, litter which had received 0.05 kg alum bird^{-1}; A0, litter which had received no alum additions.

Table 4.6: Linear regression parameters and statistics for the relationships between exchangeable Al and soil pH measured at 1 and 3-months after initiation of the incubation study for the 0-P check treatments and each P source and rate combination applied to the Frederick and Davidson soils.

P Source[†]	P rate	-----------1 Month-------------			-----------3 Months-------------		
	mg P kg^{-1}	Slope	Intercept	R^2	Slope	Intercept	R^2
		----------------------------Frederick soils-------------------------------					
Check	0	1.10	-1.60	0.990*	1.53	-3.31	0.811*
A10	65	0.82	0.20	0.619*	1.28	-2.09	0.850
A5	65	0.79	0.44	0.844*	1.06	-0.96	0.666*
A0	65	0.94	-0.33	0.956*	1.46	-3.13	0.902*
KH$_2$PO$_4$	65	1.38	-2.75	0.966*	1.01	-0.62	0.369
A10	131	0.16	4.02	0.148	0.66	1.42	0.680*
A5	131	-0.01	5.17	0.001	0.64	1.59	0.421
A0	131	0.59	1.63	0.814*	1.32	-2.34	0.752*
KH$_2$PO$_4$	131	1.19	-1.67	0.971*	1.63	-3.67	0.882*
A10	197	0.26	3.61	0.679*	0.76	0.92	0.579*
A5	197	-0.05	5.47	0.014	0.83	0.56	0.866*
A0	197	0.38	2.89	0.593*	1.06	-1.06	0.744*
KH$_2$PO$_4$	197	1.07	-0.98	0.936*	1.53	-3.31	0.811*
		----------------------------Davidson soils-------------------------------					
Check	0	2.01	-6.19	0.953*	2.75	-9.84	0.856*
A10	65	1.92	-5.67	0.889*	2.39	-8.01	0.920*
A5	65	1.83	-5.27	0.880*	2.54	-8.78	0.935*
A0	65	1.72	-4.60	0.865*	2.50	-8.54	0.983*
KH$_2$PO$_4$	65	2.16	-6.85	0.944*	2.52	-8.66	0.909*
A10	131	1.98	-6.10	0.981*	1.59	-3.76	0.371
A5	131	1.90	-5.69	0.992*	2.89	-10.52	0.811*
A0	131	2.12	-6.76	0.937*	2.19	-7.09	0.915*
KH$_2$PO$_4$	131	2.02	-6.07	0.872*	2.59	-9.12	0.682*
A10	197	1.59	-3.97	0.970*	1.43	-3.03	0.309
A5	197	0.92	-0.29	0.778*	1.48	-3.40	0.713*
A0	197	1.49	-3.48	0.959*	2.44	-8.24	0.966*
KH$_2$PO$_4$	197	2.25	-7.20	0.913*	2.59	-9.12	0.682*
A10	262	1.22	-2.00	0.931*	1.43	-3.03	0.309
A5	262	0.68	1.04	0.613*	1.48	-3.40	0.713*
A0	262	0.77	0.64	0.657*	2.44	-8.24	0.966*
KH$_2$PO$_4$	262	1.95	-5.68	0.821*	2.75	-9.84	0.856*

[†] A10, litter which had received 0.09 kg alum bird[-1]; A5, litter which had received 0.05 kg alum bird[-1]; A0, litter which had received no alum additions.

[‡]R^2 values followed by * are significant at the p<0.01 level.

Table 4.7: P values used to determine differences in the linear relationship between exchangeable Al and soil pH resulting from the A10, A5, A0 litters, and KH_2PO_4 treatments compared to the linear relationship found in the 0-P check treatments.

P Rate	Comparison†	Frederick				Davidson			
		1 Month		3 Months		1 Month		3 Months	
mg P kg-1		P Values for Slope	P Values for Intercept	P Values for Slope	P Values for Intercept	P Values for Slope	P Values for Intercept	P Values for Slope	P Values for Intercept
65	A10	0.2258	0.2295	0.5546	0.6600	0.7719	0.7526	0.1411	0.1410
65	A5	0.1429	0.1488	0.9674	0.8808	0.4893	0.5050	0.3173	0.3232
65	A0	0.2333	0.2048	0.5357	0.4943	0.3551	0.3378	0.1491	0.1500
65	KH_2PO_4	0.4905	0.5960	0.5972	0.6345	0.5791	0.6346	0.0782	0.0832
131	A10	0.0012	0.0016	0.5992	0.5532	0.8634	0.9318	0.2059	0.2161
131	A5	0.0003	0.0004	0.0930	0.0690	0.5824	0.6344	0.5550	0.5092
131	A0	0.0228	0.0241	0.1412	0.1081	0.6859	0.6946	0.1331	0.1387
131	KH_2PO_4	0.9183	0.7904	0.9497	0.9870	0.9850	0.9460	0.6428	0.6360
197	A10	0.0025	0.0028	0.4510	0.5685	0.0505	0.0559	0.4593	0.4638
197	A5	0.0002	0.0003	0.1544	0.1081	0.0007	0.0007	0.4671	0.4566
197	A0	0.0191	0.0237	0.1985	0.1442	0.0287	0.0333	0.2678	0.2658
197	KH_2PO_4	0.5667	0.4600	0.4901	0.4669	0.4553	0.5369	0.2623	0.2760
262	A10	NA	NA	NA	NA	0.0020	0.0025	0.9821	0.9795
262	A5	NA	NA	NA	NA	0.0002	0.0002	0.2517	0.2519
262	A0	NA	NA	NA	NA	0.0007	0.0007	0.7418	0.7281
262	KH_2PO_4	NA	NA	NA	NA	0.8698	0.8003	0.6462	0.6703

†A10, 0-P check treatments compared to treatments receiving litter which had received 0.09 kg alum bird[-1]; A5, 0-P check treatments compared to treatments receiving litter which had received 0.05 kg alum bird[-1]; A0, 0-P check treatments compared to treatments receiving litter which had received no alum additions; KH_2PO_4, 0-P check treatments compared to treatments receiving KH_2PO_4.

Table 4.8: Slope estimates from linear regression analysis relating H_2O extractable P measured at 1 and 12-months after application and P application rate for each of the four P sources applied to Bojac soils which received no pH adjustment (Bo1), was adjusted to a target pH of 4.5 (Bo2), and a target pH of 5.5 (Bo3).

Soil ID	P Source†	------------1 Month-----------		------------12 Month---------	
		Slope‡ mg mg^{-1}	R^2§	Slope‡ mg mg^{-1}	R^2§
Bo1	A10	0.0193de	0.849*	0.0056g	0.913*
Bo1	A5	0.0419c	0.821*	0.0138f	0.871*
Bo1	A0	0.0718b	0.918*	0.0228c	0.943*
Bo1	KH$_2$PO$_4$	0.1198a	0.975*	0.0488a	0.975*
Bo2	A10	0.0045g	0.895*	0.0058g	0.847*
Bo2	A5	0.0117f	0.874*	0.0075g	0.815*
Bo2	A0	0.0215d	0.895*	0.0173e	0.912*
Bo2	KH$_2$PO$_4$	0.0521c	0.963*	0.022cd	0.914*
Bo3	A10	0.0156ef	0.925*	0.0062g	0.890*
Bo3	A5	0.0230d	0.952*	0.0139f	0.885*
Bo3	A0	0.0519c	0.871*	0.0201d	0.901*
Bo3	KH$_2$PO$_4$	0.0790b	0.901*	0.0346b	0.958*

† A10, litter which had received 0.09 kg alum bird^{-1}; A5, litter which had received 0.05 kg alum bird^{-1}; A0, litter which had received no alum additions.
‡Slope values within a single column followed by different letters are significantly different at the 0.05 level.
§R^2 values followed by * are significant at the p<0.01 level.
¶Values followed by * indicate a significant (p<0.01) change in slope from 1 to 12-months.

Table 4.9: Slope estimates from linear regression analysis relating H_2O extractable P measured at 1 and 12-months after application and P application rate for each of the four P sources applied to Davidson soil which received no pH adjustment (Da1), was adjusted to a target pH of 4.5 (Da2), and a target pH of 5.5 (Da3).

Soil ID	P Source†	------------1 Month----------- -		------------12 Month--------- ---	
		Slope‡ mg mg^{-1}	R^2§	Slope‡ mg mg^{-1}	R^2§
Da1	A10	0.0023ef	0.556*	0.0010de	0.676*
Da1	A5	0.0032ef	0.684*	0.0013cd	0.742*
Da1	A0	0.0134a	0.830*	0.0033a	0.894*
Da1	KH$_2$PO$_4$	0.0181a	0.858*	0.0043a	0.870*
Da2	A10	0.0005g	0.162	0.0007de	0.296
Da2	A5	0.0011g	0.739*	0.0004e	0.055
Da2	A0	0.0034de	0.868*	0.0018bc	0.760*
Da2	KH$_2$PO$_4$	0.0051cd	0.868*	0.0016c	0.868*
Da3	A10	0.0020f	0.796*	0.0008de	0.420*
Da3	A5	0.0021f	0.803*	0.0013cd	0.618*
Da3	A0	0.0065bc	0.923*	0.0020b	0.772*
Da3	KH$_2$PO$_4$	0.0082b	0.879*	0.0022b	0.854*

† A10, litter which had received 0.09 kg alum bird^{-1}; A5, litter which had received 0.05 kg alum bird^{-1}; A0, litter which had received no alum additions.
‡Slope values within a single column followed by different letters are significantly different at the 0.05 level.
§R^2 values followed by * are significant at the p<0.01 level.
¶Values followed by * indicate a significant (p<0.01) change in slope from 1 to 12-months.

Table 4.10: Slope estimates from linear regression analysis relating H_2O extractable P measured at 1 and 12-months after application and P application rate for each of the four P sources applied to Frederick soil which received no pH adjustment (Fd1), was adjusted to a target pH of 4.5 (Fd2), and a target pH of 5.5 (Fd3).

Soil ID	P Source†	------1 Month-----		-----12 Month------	
		Slope‡ mg mg^{-1}	R^2§	Slope‡ mg mg^{-1}	R^2§
Fd1	A10	0.0139fg	0.887*	0.0065f	0.887*
Fd1	A5	0.0351d	0.926*	0.0092f	0.854*
Fd1	A0	0.0695b	0.907*	0.0228d	0.918*
Fd1	KH$_2$PO$_4$	0.1145a	0.938*	0.0377a	0.976*
Fd2	A10	0.0124h	0.769*	0.0076f	0.944*
Fd2	A5	0.0132gh	0.906*	0.0097f	0.885*
Fd2	A0	0.0356d	0.907*	0.0212d	0.931*
Fd2	KH$_2$PO$_4$	0.0386d	0.953*	0.019d	0.957*
Fd3	A10	0.0143f	0.957*	0.0087f	0.906*
Fd3	A5	0.026e	0.933*	0.0138e	0.907*
Fd3	A0	0.0531c	0.882*	0.0227d	0.956*
Fd3	KH$_2$PO$_4$	0.0827b	0.942*	0.031b	0.948*

† A10, litter which had received 0.09 kg alum bird^{-1}; A5, litter which had received 0.05 kg alum bird^{-1}; A0, litter which had received no alum additions.
‡Slope values within a single column followed by different letters are significantly different at the 0.05 level.
§R^2 values followed by * are significant at the p<0.01 level.
¶Values followed by * indicate a significant (p<0.01) change in slope from 1 to 12-months.

Table 4.11: Relative soil P extractability using H_2O in the Bojac and Frederick soils after 1, 3, 6, and 12 months of incubation with litter P sources.

Soil †	P Source‡	1 Month	3 Months	6 Months	12 Months	Average	LSD(p<0.05) §
		----------------Relative P extractability (%)------------					
Bo1	A0	66	43	39	44	48	16
Bo2	A0	41	109	65	80	73	23
Bo3	A0	69	68	61	69	67	NS
Fd1	A0	52	59	58	57	57	NS
Fd2	A0	89	91	101	120	100	NS
Fd3	A0	68	72	72	68	70	NS
Bo1	A10	12	12	7	14	11	NS
Bo2	A10	10	23	31	28	23	10
Bo3	A10	25	23	30	18	24	NS
Fd1	A10	10	21	20	16	17	7
Fd2	A10	21	38	39	43	36	11
Fd3	A10	20	34	24	29	27	7
Bo1	A5	21	20	15	32	22	NS
Bo2	A5	17	55	38	42	38	19
Bo3	A5	43	38	38	39	39	NS
Fd1	A5	24	21	28	14	22	NS
Fd2	A5	32	38	46	58	43	NS
Fd3	A5	38	37	42	52	42	NS
LSD (p<0.05)¶		11	21	14	17	9	

†Bo1, Bojac soil with no pH adjustment; Bo2, Bojac soil with target pH of 4.5; Bo3, Bojac soil with target pH of 5.5; Da1, Davidson soil with no pH adjustment; Da2, Davidson soil adjusted with pH of 4.5; Da3, Davidson soil with target pH of 5.5; Fd1, Frederick soil with no pH adjustment; Fd2; Frederick soil with target pH of 4.5; Fd3, Frederick soil with target pH of 5.5.

‡A10, litter which had received 0.09 kg alum bird[-1]; A5, litter which had received 0.05 kg alum bird[-1]; A0, litter which had received no alum additions.

§ LSD, Least significant difference between sampling periods; NS, not significant.

¶ LSD, Least significant difference within sampling periods

Chapter 5: Overall Conclusions

Previous research has shown that the treatment of poultry litter with alum results in decreased soluble P concentrations in the treated litter. Also, applications of alum-treated poultry litter (ATPL) to pasture systems have been shown to result in lower soil test P concentrations and surface runoff P concentrations. However, evaluation of the production and environmental consequences of using ATPL as a nutrient source, particularly when applied at rates based on current nutrient management strategies to cultivated systems, is limited. Therefore, the objectives of this research were to evaluate the impact of using ATPL as a nutrient source on the production of both field corn and tall fescue when applied at rates prescribed by current nutrient management strategies. Also, the impact of long-term applications of ATPL on the P status of soils as determined by routine soil test analyses (Mehlich 1) and surface runoff P concentrations from cultivated systems was also evaluated. The potential for elevated exchangeable soil Al and suppressed soil pH resulting from applications of ATPL to soils was also assessed. Finally, the distribution of soil P resulting from ATPL applications, as determined by sequential fractionation, was determined.

Evaluation of ATPL as a nutrient source for corn grain and tall fescue forage production showed that no significant changes in current litter management strategies are required to ensure crop productivity similar to that resulting from applications of non-treated litter (NPL). Alum-treated poultry litter appeared to provide adequate available P for optimum crop productivity even in soils with less than optimum soil test P levels. This research also demonstrated the importance of mid-season assessment of the N status of a corn crop when using poultry litter as the sole N source in the Coastal Plain of Virginia. However, the experimental design used did not allow for detailed evaluation of N availability of the ATPL and NPL sources used.

When applied at rates sufficient to supply the N requirement for corn grain production, the ATPL resulted in lower Mehlich 1 extractable P levels compared to NPL. A portion of this reduction was associated with decreased P application for the N-based-ATPL treatments resulting from the elevated N content of the ATPL. However, this reduction could also be related to the decreased P availability resulting from alum treatment, particularly when the litter was applied to Coastal Plain soils. Data collected from field experiments and laboratory incubations showed that soil pH can have a profound impact on the relative H_2O extractability of P applied in ATPL and NPL. This finding demonstrated the importance of assessing differential impacts of P source applications on soil pH when evaluating the availability of P after incorporation into soils. Data from an incubation study, in which two different ATPL sources were compared, showed that neither the Al:P ratio nor the soluble P content of litter would explain differences in the H_2O extractability in soils treated with the two ATPL sources. This result suggests that although the soluble P content of poultry litter may be a useful measure of potential runoff P transport when surface applied, caution should be used when using this litter characteristic to assess the availability in soils after incorporation.

The use of simulated rainfall showed that the suppressed soil test P concentrations in soils receiving ATPL resulted in decreased runoff P concentrations 1-yr after P source application to cultivated soils. Rainfall simulations on plots 2-days after P source

application confirmed previous research showing that ATPL applications result in lower soluble P concentrations in runoff. However, these simulations also showed that when applied to cultivated systems without incorporation, total P losses were related to litter particle losses. Therefore, total P losses in runoff from ATPL treatments were not reduced compared to NPL treatments because litter particle loss was not affected by litter source. These data demonstrate that the primary benefit of ATPL applications to cultivated systems results from the decreased P status of treated soils. Also, prevention of litter particle loss to surface runoff shortly after application is needed to realize the benefit of decreased P solubility in ATPL.

Previous research showed elevated concentrations of soluble Al in ATPL sources. However in this study, applications of ATPL did not result in elevated concentrations of Al in plant tissue or soils collected from the field trials. These results show that long-term application of ATPL does not pose an increased risk of Al toxicity to crops. A laboratory incubation utilized to evaluate short-term impacts of ATPL application showed that its application does not increase exchangeable Al concentrations in soils during a 1-year period after application. In addition, differences in soil pH when comparing soils treated with ATPL and NPL appeared to be a function of the rate of litter applied and the total N supplied by the P-based rates used in the incubation rather that the rate of Al or S applied.

Evaluation of P forms present in soils, as determined by sequential fractionation, revealed that ATPL applications result in reduced concentrations of H_2O and $NaHCO_3$ extractable inorganic P compared to NPL and TSP. These decreases in labile P forms were consistent with previous research. A unique finding of this research was the presence of elevated organic P in the 0.1 M NaOH extraction. Unlike the suppressed concentrations of inorganic P extracted using H_2O and 0.5 M $NaHCO_3$, which only occurred in the N-based application of ATPL, the increase in 0.1 M NaOH-extractable organic P occurred at each application rate. Because this fraction was found in 2-yr crop removal-based treatments which had not received ATPL for 2 years prior to sampling it appears that this P fraction is persistent in soils. Future research may focus on evaluating the mechanisms that control the accumulation of this P fraction in soils receiving ATPL in order to better understand the mechanisms by which alum treatment of poultry litter affects soil P distribution.

Data presented here confirm the usefulness of treating poultry litter with alum in reducing P availability in soils for the purpose of minimizing the impact of poultry litter applications on surface water quality. This research also showed that using ATPL as a nutrient source in Virginia will not require alteration of current nutrient management strategies. However, future research should focus on the persistence of the insoluble P compounds formed in ATPL following application to soils. Data collected show that these compounds can be quantified, even in soils with relatively high P sorption capacities. However, these data do not confirm the long-term stability of these compounds in soil. The quantification of these compounds through sequential extraction in both the litter applied and treated soils would allow for a better understanding of the persistence of these compounds. Also of interest is the mechanism by which these compounds are formed in litter. Previous research has focused on transformations of inorganic P in litter resulting from alum applications however the data presented here

show that the occurrence of organic P transformations may be important mechanisms by which alum-treatment of poultry reduces P availability.