Impact of Gypsum Applied to Grass Buffer Strips on Reducing Soluble P in Surface Water Runoff

D. B. Watts* and H. A. Torbert USDA-ARS

The threat of P transport from land applied manure has resulted in water quality concerns. Research was conducted to evaluate gypsum as a soil amendment applied to grass buffer strips for reducing soluble P in surface runoff. A simulated concentrated flow was created in an established tall fescue (*Festuca arundinacea* Schreb.) pasture. Poultry litter (PL) was applied at a rate of 250 kg N ha^{-1} to the upper 3.05 m of each plot, while gypsum was applied at rates of 0, 1, 3.2, and 5.6 Mg ha–1to the lower 1.52 m of the plot functioning as a grass buffer strip. Two 30-min runoff events (~4 L min^{-1}) were conducted, immediately after PL application and 4 wk later to determined soluble P concentration in the surface water samples. The greatest concentration of soluble P was in the runoff event occurring immediately after the PL application. Gypsum applied to grass buffer strips was effective in reducing soluble P concentrations (32–40%) in surface runoff, while the untreated buffer strip was somewhat effective in reducing soluble P (18%). No significant differences were observed between gypsum rates, suggesting that land managers would achieve the greatest benefit from the lowest application rate (1 Mg ha^{-1}). In the second runoff event, although concentrations of soluble P in the surface water runoff were greatly reduced, the effect of gypsum had disappeared. Thus, these results show that gypsum is most effective in reducing the initial P losses from PL application when applied to grass buffer strips. The information obtained from this study may be useful in aiding land managers in developing management practices that reduce soluble P loss at the edge of a field.

Published in J. Environ. Qual. 38:1511–1517 (2009).
doi:10.2134/jeq2008.0378
Received 20 Aug. 2008.
*Corresponding author (dwatts@ars.usda.gov).
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

In recent years, concerns for environmental quality have prompted interest in the development of agricultural practices that minimize nutrient loss to the environment. In a general assessment conducted by the EPA, 45% of river miles, 47% of lake acres, and 32% of estuarine waters were reported to be impaired, primarily from eutrophication (USEPA, 2002). Specifically, P has been identified as the most critical nutrient impacting freshwater eutrophication, with agriculture being a major contributor (USEPA, 1996; Sharpley et al., 1999). While most of the water quality impairment from agriculture is a result of management and land use, evidence indicates that water quality issues resulting from the growing animal production industry are also increasing (USEPA, 1996). A study performed by the USGS found that conversion to larger and more concentrated animal operations between 1982 and 1997 contributed to the decrease in water quality (Gollehon et al., 2001). Present estimates indicate that the animal industry accounts for 16% of water quality impairment from agricultural production (USEPA, 2001); this figure is projected to increase in the coming years. Because of these concerns, in the southeastern United States where the poultry industry is steadily increasing, management and disposal of poultry waste is fast becoming top priority. Therefore, BMPs must be developed to prevent environmental degradation.

In southeastern United States, the poultry industry makes up a significant portion of the total animal production (USDA National Agricultural Statistics Service, 2007). Georgia, Arkansas, and Alabama (the largest poultry producer in the United States) produce approximately 1.4 billion (16%), 1.2 billion (13%), and 1.1 billion (11%), of the nation's 8.9 billion broilers (USDA National Agricultural Statistics Service, 2007), respectively, generating 11.4 million tonnes of broiler litter (1.5 kg litter/broiler) each year (Mitchell and Tu, 2005). At approximately 11% of the nation's output, Alabama is ranked third in the nation in broiler production (Mitchell and Tu, 2005). The broiler industry, mainly concentrated in the Sand Mountain region of northern Alabama produces approximately 1.9 million tonness of poultry litter annually (Kingery et al., 1994). Proper disposal of this poultry litter is important because it contains high amounts of P. Estimates indicate that most P in poultry litter is inorganic (>75%) and is plant available at the time of application (Eghball et al., 2002; Sharpley and Moyer, 2000). Sharpley and Moyer (2000) reported that, of the inorganic fraction, 80% was water-extractable. Thus, improper disposal of waste generated

USDA-ARS, National Soil Dynamics Lab., 41 S. Donahue Dr., Auburn, AL 36832.

Abbreviations: BMP, best management practice; PL, poultry litter.

from poultry production can be a major threat to surface waters, thereby causing eutrophication resulting from soluble P (Sharpley, 1995; Daniel et al., 1998). This increases the pressure on producers and resource managers to dispose of this waste in an environmentally friendly way to prevent negative water quality impacts from animal production.

Historically, the most common disposal practice of poultry litter has been land application to pastures. There are strong indications that this practice will continue to increase, partly as a result of the growing animal industry and the increasing cost of inorganic fertilizer. Thus, developing BMPs is imperative to preventing environmental degradation. If implemented properly, BMPs can decrease the transport of organic and inorganic nutrients. The effectiveness of a BMP is determined by its ability to decrease or even remove the nutrient load and concentration in runoff water. Management practices such as grass buffer strips located at the edge of an agricultural field seem promising in reducing nutrient concentration in surface runoff from land application of poultry litter. Grass buffer strips along the side of ditches or fields have been used for years as a means of reducing nutrient transport from erosive soil and have been encouraged by the Natural Resource Conservation Service (Magette et al., 1989; NRCS, 1999; Dorioz et al., 2006). These buffer zones can be beneficial in maintaining water quality, in particular, by slowing down, stopping, or preventing the transport of soluble nutrients from flowing in surface waterways via runoff (Vought et al., 1995; NRCS, 1997; Heathwaite et al., 2000; Dosskey, 2001; Benoit et al., 2004; Dorioz et al., 2006). Although they have been shown to reduce sediment movement and some soluble nutrients, grass buffer strips are not very effective at reducing high amounts of soluble nutrients (Dorioz et al., 2006). Thus, improving the effectiveness of grass buffer strips could provide better protection of nearby water bodies.

Similarly, the use of gypsum ($CaSO_4$) as a soil amendment seems promising as a method for reducing the loss of soluble P. Studies have shown that the addition of gypsum can effectively reduce soluble P in runoff from soil with high soil test P (Stout et al., 1998). Gypsum reduces P losses by increasing the aggregation of soil particles, thereby reducing the amount of P carried with sediment (McCray and Sumner, 1990). Brauer et al. (2005) suggested that a reduction in P losses can arise from the formation of insoluble Ca-phosphate complex when gypsum reacts with soluble phosphate. The result is an insoluble hydroxyapatite and fluorapatite formed when soluble P reacts with Ca (Lindsay, 1979). As air quality standards continue to increase to comply with EPA's Clean Air Interstate Rule, so will the supply of gypsum, since gypsum is produced in large quantities as a by-product of gas desulfurization systems used to reduce air pollution in coal-burning power plants.

Transport of P from land application of manure poses a major threat of accelerated eutrophication of surface waters. Therefore, development of BMPs that minimize the environmental impact of P loss from animal waste management is needed. The use of buffer strips in conjunction with soil amendments seems promising as a low-cost option. Thus, the objective of this study was to evaluate effectiveness of grass buffer strips and gypsum amendments in reducing the loss of P from land-applied poultry litter in agricultural runoff.

Materials and Methods

Experimental Site Description

The experiment was conducted at the Auburn University, Sand Mountain Research and Extension Center in the Appalachian plateau region of Northeast Alabama in the summer of 2006. Runoff plots were established on a hillslope with a uniform gradient of approximately 5%, which is representative of the local topography. The soil type was a Hartsells fine sandy loam (fine-loamy siliceous, subactive, thermic Typic Hapludults). Each plot was 1.52 m wide and 4.88 m long with the long axis oriented parallel to the flow path. Galvanized metal plot borders extended approximately 13 cm (5 in) below the soil surface and 7 cm above the soil. A galvanized metal trough was located on the down-slope end of each plot to collect and transport runoff to a collection point. Runoff plots were constructed on a permanent pasture (ungrazed) used for tall fescue hay production. The plots were mowed before conducting the experiment and vegetation removed leaving the grass with a sward height of approximately 15 cm.

Concentrated Flow Dispersion Devices

Water dispersion devices as described by Wolfe et al. (2000), which provided an even distribution of water runoff equivalent to 124 mm h^{-1}, were used to create a runoff event (concentrated flow of water). These devices were placed upslope of each plot (Fig. 1). The dispersion devices were constructed by the National Soil Dynamics Laboratory Machine Shop. These devices consisted of aluminum boxes with dimensions of 1.0 m long by 0.5 m wide by 0.5 m high. Before use, these devices were calibrated to ensure accurate runoff intensities. The runoff devices were designed to create a concentrated flow of water over the plots. Thus, this device creates a continuous stream of water that is similar to that of a high intensity rainfall event under runoff conditions. McDowell and Sharpley (2002) successfully used similar runoff boxes to evaluate overland flow of water for P transport across different soil textures under laboratory conditions. Water used to create the concentrated flow, obtained from a nearby groundwater well, was pumped into a 950-L holding tank and used within 2 h of pumping. No appreciable amount of P concentration was in the well water.

Treatments and Sample Analysis

The experimental layout of the study was designed to assess the effectiveness of gypsum applied as a soil amendment to grass buffer strips at the edge of a field. Each plot was divided into two sections. The upper portion (upslope) of the plot was 3.05 m, which represented a pasture fertilized with poultry litter. The lower portion (downslope) of the plot was 1.52 m, which represented a grass buffer strip at the edge of an agricultural field (Fig. 1). The upslope portion of the plot was separated from the downslope portion by a 0.3048-m buffer to allow sampling for surface runoff from the upslope portion of

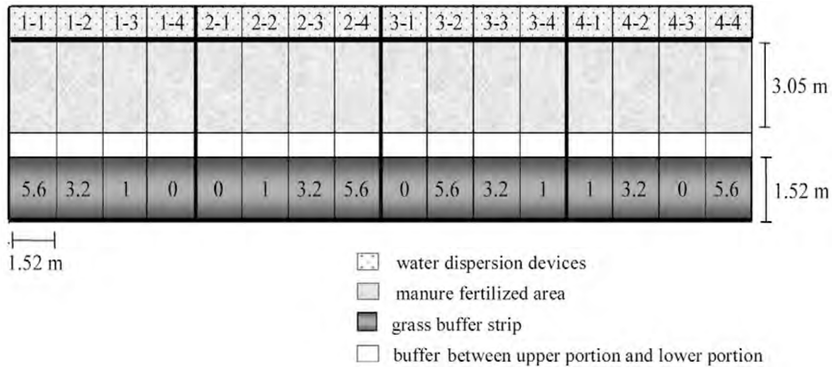

Fig. 1. Experimental layout of runoff plots. Manure was applied upslope to all plots at a rate of 250 kg N ha^{-1} and gypsum was applied downslope at rates of 0, 1, 3.2 and 5.6 Mg ha^{-1} to grass buffer strips, water dispersion devices, manure fertilized area, and grass buffer strip.

the plot. Sampling of the upslope portion was performed using a chrome plated transfer pump (Wayne Reliantone Transfer Utility Pump, Harrison, OH) connected to a standard garden hose fitted a water suction attachment. Poultry litter used in this study was collected from a local poultry production facility and consisted of poultry manure and a bedding material mixture. Poultry litter was applied directly to the soil surface at a rate of 250 kg N ha^{-1}. Following the addition of poultry litter, a surface application of commercial farm-grade gypsum ($CaSO_4$) was applied to the buffer strips at rates of 0, 1, 3.2, and 5.6 Mg ha^{-1}. The buffer strip containing gypsum was slightly moistened to move the gypsum down to the soil surface before the runoff event.

This study consisted of two separate runoff events. Each runoff event was conducted for a minimum of 30 min. Once runoff was initiated, water samples were collected manually at 10-min intervals (0, 10, 20, and 30 min) for the duration of the event. The first runoff event occurred immediately after the application of poultry litter and gypsum to the plots. A second study was conducted 4 wk later, in which another 30-min runoff event was evaluated on the same plots. The plots were left uncovered during the 4-wk period between the first and second runoff study to simulate natural field conditions. Rainfall data between the first and second surface runoff events are presented in Fig. 2. Rainfall intensity was not high enough to create a runoff between the first and second runoff event. During each simulated runoff event, water samples were taken directly below the upslope portion of the plot (in the 0.3048-m buffer between the upslope and downslope portion), which represented a pasture fertilized with poultry litter, and at the bottom of the plot below the grass buffer strip.

Immediately after collection, water samples were acidified with concentrated HCl and frozen until analyzed. Water samples were filtered through a 0.45-µm membrane and analyzed for soluble P by the Auburn University Soil Testing Laboratory using the ICAP (Hue and Evans, 1986). Samples of the poultry litter used in this study were also collected at the time of application, and chemical analyses were conducted for total N, P, K, Ca, Mg, and micronutrient concentrations by Auburn Soil Testing Laboratory, using procedures outlined by Hue and Evans (1986). Poultry litter characteristics are presented in Table 1.

Statistical Analysis

The experimental design of this study was a randomized complete block (with four replicates by four chemical amendments) shown in Fig. 1. Statistical analysis was performed using the Mixed Procedure of SAS (Littell et al., 1996). Means were separated using LSD value; a significance level of $\alpha < 0.10$ was established a priori. Analysis of variance was performed to evaluate the main effects of buffer strips, soil amendment, and time, as well as interaction between buffer strips, and soil amendments, and time.

Results and Discussion

The focus of this study was to evaluate the impact that gypsum added to grass buffer strips had on reducing the amount of soluble P in surface water runoff. Also, the residual effect after 1 mo of gypsum addition was evaluated through a second runoff event. This study is unique compared to others in that it evaluated the effect of soil amendments applied to grass buffer strips to restrict and trap soluble P from large runoff events. In this study, a concentrated flow was generated by creating a sheet of water that flowed over the plots at a rate of 4 L min^{-1}, or greater, to simulate conditions found in grass buffer strips during high intensity rainfall events. Thus, an average runoff volume of approximately 163 L (44 mm h^{-1}) for the entire 30-min runoff event was created. In general, analyses for surface water runoff in this study indicated no significantly different interactions between soluble P concentration and time ($P < 0.05$) at most instances (Table 2). Thus, in the succeeding text the main treatment effects of soluble P concentration and time are discussed separately.

Reduction in Soluble Phosphorus following Initial Poultry Litter Application

In the first part of the study, soluble P movement in a concentrated flow of water was evaluated shortly after poultry litter application. The use of grass buffer strips had a distinct impact on the nutrient concentration observed in surface water runoff, significantly decreasing the concentration of soluble P. Mean nutrient concentrations of soluble P as affected by buffers strips are shown at each sampling time in Table 3. Averaged across

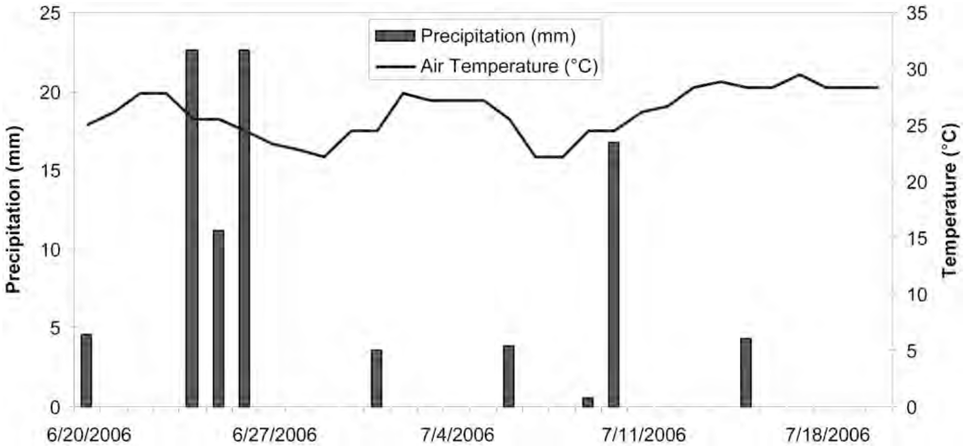

Fig. 2. Mean air temperature and precipitation data between the first and second runoff study.

Table 1. Poultry litter characterististics on a dry-weight basis.

N	P	K	Ca	Mg	Cu	Fe	Mn	Zn	B	Co	Al	Moisture
		g kg^{-1}						mg kg^{-1}				g 100 g^{-1}
26.7	45.6	28.9	33.5	6.7	53	1617	496	425	53	323	2073	21.8

Table 2. Summary of the analysis of variance for experimental effects on soluble P concentration in runoff water for the initial and second surface runoff events.

Source of variation	df	Soluble P concentration *P* value
Initial runoff event		
Time	3	0.0001
Treatment	4	0.0194
Time × treatment	12	0.9767
Second runoff event	3	0.0079
Time	4	0.0158
Time × treatment	12	0.9724
Initial vs. second runoff	1	<0.0001

Table 3. Mean soluble P concentration in runoff water for the initial runoff event as affect by 0, 1, 3.2, and 5.6 mg ha^{-1} of gypsum added to the grass strips and without gypsum and buffer strip treatment as the control.

Gypsum rate	Mean concentration of soluble P Sample time (min) 0	10	20	30	Mean
Mg ha^{-1}			Mg L^{-1}		
0	16.29	20.97	12.64	8.67	14.84 a†
0 + buffer	10.42	15.90	13.53	8.86	12.17 b
1 + buffer	7.87	14.78	9.95	7.29	9.97 c
3.2 + buffer	7.79	13.46	10.15	6.46	9.47 c
5.6 + buffer	7.54	13.38	8.00	6.56	8.87 c
Mean	9.98 a	5.70 b	10.85 a	7.57 a	

† Means without a letter in common differ significantly at the 0.10% probability level.

each sampling time, soluble P losses were reduced by 18% as a result of the grass buffer strip compared to controls with no buffer strip treatment (Fig. 3), indicating that grass buffer strips can be effective in reducing soluble P. Previous research has shown that grass buffer strips can act as a filter, restricting the movement of surface water and the associated soil particles, thus reducing the velocity of the water movement (Bishnoi, 1991; Pearce et al., 1997; Dorioz et al., 2006). This suggests that, in this study, the soluble P in solution resulting from the addition of poultry litter had more time to react with soil particles, thereby reducing the solubility. Furthermore, others have also reported that grass buffer strips can reduce soluble P as a result of increased rooting channels, causing an increase in infiltration (Magette et al., 1989; Dillaha et al., 1989). Thus, in this study, some of the soluble P associated with particulate matter in the poultry litter was probably removed by the soil as the water percolated through.

The use of gypsum as a soil amendment also significantly impacted soluble P loss in surface water runoff. Addition of gypsum to grass buffer strips significantly reduced the soluble P concentration compared to the grass buffer strip alone. Table 3 shows that immediately soluble P was reduced as a result of gypsum addition from time 0 through the duration of the experiment. No significant differences were observed among gypsum rates. Although, no significant differences were observed between gypsum rates, a greater reduction in soluble P was achieved as the rate of gypsum increased. Averaged across each sampling time, a reduction in soluble P losses was achieved between 33% (1 Mg ha^{-1}) and 40% (5.6 Mg ha^{-1}) for the gypsum treatment compared to the control (Fig. 3). This phenomenon was probably a result of the gypsum converting the soluble P desorbed from the poultry litter to a less soluble Ca-P complex. These findings are in accordance with the findings of other researchers who reported a reduction of soluble P with the application of gypsum, however, most of the previous research findings mixed the gypsum with the manure (Moore and Miller, 1994; Anderson et al., 1995; Dao, 1999; Dao et al., 2001; Dou et al., 2003) or added the gypsum over the applied manure (Torbert et al., 2005). This study shows that application of gypsum to grass buffer strips can also achieve a reduction in soluble P, thereby reducing initial loss of P to the environment. These results suggest that soil amendments can be applied to buffer strips or filter strips located at the edge of a field rather than to an entire field

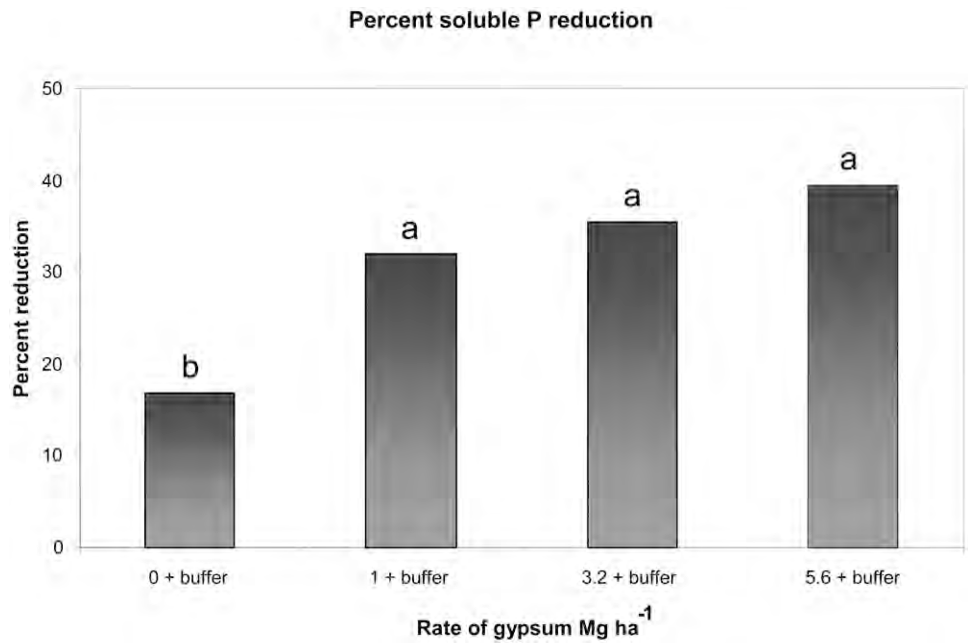

Fig. 3. Percent reduction of soluble P for the initial surface runoff event for 0, 1, 3.2, and 5.6 g ha^{-1}added to grass buffer strip.

area. This practice would be more beneficial to a producer due to reduction in the overall cost and time associated in using a soil amendment to reduce P loss.

Means for soluble P concentration, as affected by gypsum application rates and grass buffer strips, observed during the runoff study for each sampling time are presented in Table 3. No significant interactions between treatments and time were observed; this was probably due to the fact that the reduction in soluble P as affected by treatment was uniform over time (Table 3). However, there was a main effect for treatment and time. The highest observed soluble P concentration from the manure application was 10 min after runoff began. Similar results were reported by Vadas et al. (2004) who evaluated surface water runoff from soil fertilized with poultry litter; these authors attributed this phenomenon to the physical breakdown of litter clumps during the rainfall simulation, suggesting that the initial water from surface runoff is responsible for releasing most of the soluble P during the initial poultry litter wetting. Soluble P concentration peaked at the 10-min time interval and decreased over time thereafter. This decrease in P concentration can be attributed to a decrease in desorption of P from the litter and an increase in P adsorption to the soil surface. Also, a decrease in the initial high P concentration observed after the first 10 min probably resulted from dilution of the soluble P over time with the addition of continuous runoff water. This is similar to the finding of others (Pote et al., 1996; McDowell and Sharpley, 2002, 2003). Thus, these results suggest that controlling nutrient concentrations in surface water runoff is most critical within the first 10 min after initiation of a runoff event.

Reduction of Soluble Phosphorus One Month after Application

In the second rainfall event, the study was re-evaluated to determine whether the grass buffer strip and gypsum treatments could potentially extend reduction of the soluble P concentration in surface water runoff. To achieve this, a second runoff event was conducted on the same plots 4 wk after the first event. This was conducted to give some insight as to what the residual impacts of gypsum amendments added to grass buffer strips would be on the reduction of soluble P after poultry litter application. In essence, we wanted to know whether the potential benefits of gypsum additions would persist.

The concentration of soluble P in the second surface water runoff significantly decreased from the initial runoff experiment (Table 4). This indicates that most of the soluble P had adsorbed to soil particles, decreasing the potential for transport in runoff water. This is similar to the findings of Kleinman and Sharpley (2003) who attributed the observed decrease in soluble P concentrations in succeeding runoff events that occurred 3, 10, and 24 d after broadcast manure application to the adsorption of P to soil particles. Edwards and Daniels (1994) showed that soluble P concentrations were similar to background concentrations after two runoff events from rainfall simulations. Although the soluble P concentration had decreased substantially in the second experiment compared to the first, the amount of soluble P observed in plots under the highest rate of gypsum increased (Table 4). This phenomenon was observed at each sampling interval. This was the opposite of what was observed in the initial rainfall event, suggesting that the gypsum used to adsorb the soluble P in the first rainfall event had dissipated, reducing the binding capacity of the sorbing material. This also suggests that soluble P bound in the treatment with the highest gypsum rate remained in the field instead of being lost down stream. Thus, more soluble P was lost from the treatment in the second runoff event with the highest gypsum rate because more P was present. In essence, the effectiveness of gypsum as a sorbing material for reducing soluble P appears to be temporary and thus, does not appear to

Table 4. Mean soluble P concentration in runoff water for the second runoff event as affect by 0, 1, 3.2, and 5.6 mg ha^{-1} of gypsum added to the grass strips and without gypsum and buffer strip treatment as the control.

Gypsum rate	Mean concentration of soluble P Sample time (min) 0	10	20	30	Mean
Mg ha^{-1}	Mg L^{-1}				
0	3.46	3.88	2.98	2.66	3.25 a†
0 + buffer	3.59	3.57	3.04	2.50	3.18 a
1 + buffer	4.68	2.97	2.46	2.42	3.13 a
3.2 + buffer	4.05	3.59	2.95	2.78	3.34 a
5.6 + buffer	5.10	4.25	4.02	3.94	4.33 b
Mean	4.18 a	3.65 ab	3.09 b	2.86 b	

† Means without a letter in common differ significantly at the 0.10% probability level.

be a long-term solution. Although the effectiveness of gypsum as a sorbing material had diminished, the amount of soluble P was reduced dramatically in the subsequent runoff event.

This experiment evaluated the effect of gypsum used as a soil amendment, applied to grass buffer strips for reducing P in surface water runoff. This study clearly indicates that gypsum can be used as a soil amendment to reduce surface runoff of P in the first major rainfall event. Further research is needed to evaluate the long-term binding capacity of gypsum and other soil amendments (alum-$AlSO_4$, ferrous sulfate-$FeSO_4$, lime-$CaCO_3$ etc.) as agents for reducing soluble P in surface water runoff.

Soluble P concentration decreased over time in the second runoff event compared to the initial runoff event. This was clearly demonstrated in Tables 3 and 4. The only exception was the samples without a buffer strip. Surface water runoff for this treatment experienced an increase in soluble P at the 10-min interval, although this was less evident than in the initial rainfall event. As for the other treatments, plots with buffer strips and gypsum amendments, a decrease in soluble P concentration was observed starting at time 0 through the 30-min duration. This suggests that the soluble P from the poultry litter amended soil had reached a steady state. Also, these results provide evidence that the most crucial time for reducing the amount of P released into surface water runoff from poultry litter is during the first runoff event. Afterward, subsequent runoff events would probably decrease soluble forms of P in poultry litter because most of the P would have already been released from the litter in initial events. As a result, only a small fraction of the residual P would be released and as the runoff event persists over time, dilution of the residual poultry litter would occur.

This study is an example of a high intensity runoff event or channel flow that would be experienced in an agricultural field. During most rainfall events, nutrient transport concentrations and surface water runoff volumes probably would not be as intense as in this study. In a normal year, major runoff events, creating concentrated flows in pastures on Coastal Plain soils (sandy texture), are only experienced once or twice a year. In most instances, smaller rainfall events would release some of the soluble P in the poultry litter over time, thus giving the P in poultry litter time to react with soil particles before a high intensity rainfall event occurs. Under the set of circumstances experienced in this experiment, the use of BMPs such as grass buffer strips in conjunction with gypsum can be an effective practice used to prepare for the worst conditions.

Conclusions

Phosphorus is the second most limiting plant nutrient. Due to its low solubility compared to N, P it is often considered to be a scarce nutrient for primary production in both terrestrial and aquatic environments. Hence, the application of organic amendments such as poultry litter, which contains high amounts of soluble P, can contribute to impairment in water quality if lost in surface water runoff.

This study demonstrated that management practices using grass buffer strips in conjunction with gypsum as a soil amendment can reduce the detrimental loss of soluble P in surface water runoff. The initial runoff on the day of poultry litter application resulted in the greatest loss in soluble P. In the subsequent runoff event (4 wk after the initial event), soluble P loss was greatly reduced, implying that controlling P from the initial rainfall event was the most important. Our results showed that the grass buffer strips were somewhat effective in reducing the amount of soluble P and the application of gypsum to grass buffer strip was highly effective. The effectiveness of gypsum applied to grass buffer strips was most evident in the initial runoff event. By the second runoff event, the effectiveness of gypsum was less evident, suggesting that gypsum is only a short-term solution for reducing soluble P. However, reducing the initial loss of soluble P in the first runoff event provided an opportunity for a natural reduction of P to occur, minimizing or even eliminating the amount of soluble P contributing to surface waters down stream. Gypsum's effectiveness was not dependent on the quantity of material used in this study, suggesting that land managers would achieve the greatest benefit from the lowest application rate. Thus, gypsum as a soil amendment could be used to reduce soluble P loss in surface water runoff that occurs shortly after poultry litter application.

References

Anderson, D.L., O.H. Tuovinen, A. Faber, and I. Ostrokowski. 1995. Use of soil amendments to reduce soluble phosphorus in dairy soils. Ecol. Eng. 5:229–246.

Benoit, P., C. Souiller, I. Madrigal, V. Pot, B. Re´al, Y. Coquet, C. Margoum, B. Laillet, H. Blanco-Canqui, C.J. Gantzer, S.H. Anderson, and E.E. Alberts. 2004. Grass barriers for reduced concentrated flow induced soil and nutrient loss. Soil Sci. Soc. Am. J. 68:1963–1972.

Bishnoi, U.R. 1991. Management effects of crops and crop strip widths on crop yield and conservation of soil and moisture on a limited-resource farm. J. Soil Water Conserv. 67:147–150.

Brauer, D., G.E. Aiken, D.H. Pote, S.J. Livingston, L.D. Norton, T.R. Way, and J.H. Edwards. 2005. Amendments effects on soil test phosphorus. J. Environ. Qual. 34:1682–1686.

Daniel, T.C., A.N. Sharpley, and J.L. Lemunyon. 1998. Agricultural phosphorus and eutrophication: A symposium overview. J. Environ. Qual. 27:251–257.

Dao, T.H. 1999. Coamendments to modify phosphorus extractability and nitrogen/phosphorus ratio in feedlot manure and composted manure. J. Environ. Qual. 28:1114–1121.

Dao, T.H., L.J. Sikora, A. Hamasaki, and R.L. Chaney. 2001. Manure phosphorus extractability as affected by aluminum and iron by-products and aerobic composting. J. Environ. Qual. 30:1693–1698.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural non point source pollution control. Trans. ASAE 32:513–519.

Dorioz, J.M., D. Wang, J. Poulenard, and D. Trevisan. 2006. The effect of grass buffer strips on phosphorus dynamics-A critical review and synthesis as a basis for application in agricultural landscapes in France. Agric. Ecosyst. Environ. 117:4–21.

Dosskey, M.G. 2001. Toward quantifying water pollution abatement in response to installing buffers on crop land. Environ. Manage. 28:577–598.

Dou, Z., G.Y. Zhang, W.L. Stout, J.D. Toth, and J.D. Ferguson. 2003. Efficacy of alum and coal combustion by-products in stabilizing manure phosphorus. J. Environ. Qual. 32:1490–1497.

Edwards, D.R., and T.C. Daniel. 1994. Quality of runoff from fescuegrass plots treated with poultry litter and inorganic fertilizer. J. Environ. Qual. 23:579–584.

Eghball, B., B.J. Weinhold, J.E. Gilley, and R.A. Eigenberg. 2002. Mineralization of manure nutrients. J. Soil Water Conserv. 57:470–473.

Gollehon, N., M. Caswell, M. Ribaudo, R. Kellogg, C. Lander, and D. Letson. 2001. Confined animal production and manure nutrients. AIB-771, June. USDA, Econ. Res. Serv., Washington, DC.

Heathwaite, L., A.N. Sharpley, and W.J. Gburek. 2000. A conceptual approach for integrating phosphorus and nitrogen management at watershed scales. J. Environ. Qual. 29:158–166.

Hue, N.V., and C.E. Evans. 1986. Procedures used for soil and plant analysis by the Auburn University Soil Testing Laboratory. Auburn Univ., Auburn, AL.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. J. Environ. Qual. 23:139–147.

Kleinman, P.J.A., and A.N. Sharpley. 2003. Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. J. Environ. Qual. 32:1072–1081.

Lindsay, W.L. 1979. Chemical equilibria in soils. John Wiley & Sons, New York.

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS system for mixed models. SAS Inst., Cary, NC.

Magette, W.L., R.B. Brinsfield, R.E. Palmer, and J.D. Wood. 1989. Nutrient and sediment removal by vegetated filter strips. Trans. ASAE 32:663–667.

McCray, J.M., and M.E. Sumner. 1990. Assessing and modifying Ca and Al levels in acid subsoils. Adv. Soil Sci. 14:45–75.

McDowell, R.W., and A. Sharpley. 2002. Phosphorus transport in overland flow in response to position of manure application. J. Environ. Qual. 31:217–227.

McDowell, R.W., and A. Sharpley. 2003. The effects of soil carbon on phosphorus and sediment loss from soil trays by overland flow. J. Environ. Qual. 32:207–214.

Mitchell, C.C., and S. Tu. 2005. Long-term evaluation of poultry litter as a source of nitrogen for cotton and corn. Agron. J. 97:399–407.

Moore, P.A., Jr., and D.M. Miller. 1994. Decreasing phosphorus solubility in poultry litter with aluminum, calcium and iron amendments. J. Environ. Qual. 23:325–330.

NRCS. 1997. Technical guide. USDA Natural Resource and Soil Conserv. Serv., Washington, DC.

NRCS. 1999. The national conservation buffer initiative. USDA Natural Resources Conserv. Serv., Washington, DC.

Pearce, R.A., M.J. Trlica, W.C. Leininger, J.L. Smith, and G.W. Frasier. 1997. Efficiency of grass buffer strips and vegetation height on sediment filtration in laboratory rainfall simulation. J. Environ. Qual. 26:139–144.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855–859.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. J. Environ. Qual. 24:920–926.

Sharpley, A.N., W.J. Gburek, G. Folmar, and H.B. Pionke. 1999. Sources of phosphorus exported from an agricultural watershed in Pennsylvania. Agric. Water Manage. 41:77–89.

Sharpley, A.N., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. 29:1462–1469.

Stout, W.L., A.N. Sharpley, and H.B. Pionke. 1998. Reducing soil phosphorus solubility with coal combustion by-products. J. Environ. Qual. 27:111–118.

Torbert, H.A., K.W. King, and R.D. Harmel. 2005. Impact of soil amendments on reducing phosphorus losses from runoff in sod. J. Environ. Qual. 34:1415–1421.

USEPA. 1996. Environmental indicators of water quality in the United States. EPA 841- R-96–002. USEPA, Office of Water (4503F), U.S. Gov. Print. Office, Washington, DC.

USEPA. 2001. National pollutant discharge elimination system permit regulation and effluent limitations guidelines and standards for concentrated animal feeding operations; proposed rule. Fed. Regist. 66:2960–3145.

USEPA. 2002. National water quality inventory: Report to congress 2002 Reporting cycle. Chapter 2, p. 14, and Chapter 3, p. 21. Available at http://www.epa.gov/305b/(verified 13 Mar. 2009). Office of Water, Washington, DC.

USDA National Agricultural Statistics Service. 2007. United States Department of Agriculture, US and State data. Available at http://www.nass.usda.gov/ (verified 13 Mar. 2009). USDA, Washington, DC.

Vadas, P.A., J.J. Messinger, L.J. Sikora, J.P. McMurty, and A.E. Sefton. 2004. Effect of poultry diet on phosphorus in runoff from soils amended with poultry manure and compost. J. Environ. Qual. 33:1845–1854.

Vought, L.B.M., G. Pinay, A. Fuglsang, and C. Ruffinoni. 1995. Structure and function of buffer strips for a water quality perspective in agricultural landscapes. Landscape Urban Plan. 31:323–331.

Wolfe, J.E., K.N. Potter, and D.H. Hoffman. 2000. A device for simulating overland flow. J. Soil Water Conserv. 55:102–104.