Subsurface Application of Poultry Litter and Its Influence on Nutrient Losses in Runoff Water from Permanent Pastures

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Environmental pressure to reduce nutrient losses from agricultural fields has increased in recent years. To abate this nutrient loss to the environment, better management practices and new technologies need to be developed. Thus, research was conducted to evaluate if subsurface banding poultry litter (PL) would reduce nitrogen (N) and phosphorus (P) loss in surface water runoff using a four-row prototype implement. Rainfall simulations were conducted to create a 40-min runoff event in an established bermudagrass (*Cynodon dactylon* L.) pasture on soil types common to the Coastal Plain and Piedmont regions. The Coastal Plain soil type was a Marvyn loamy sand (fine-loamy, kaolinitic, thermic Typic Kanhapludults) and the Piedmont soil type was a Hard Labor loamy sand (fine, kaolinitic, thermic Oxyaquic Kanhapludults). Treatments consisted of surface- and subsurface-applied PL at a rate of 9 Mg ha^{-1}, surface broadcast–applied commercial fertilizer (CF; urea and triple superphosphate blend) at the equivalent N (330 kg N ha^{-1}) and P (315 kg N ha^{-1}) content of PL, and a nonfertilized control. The greatest loss for inorganic N, total N, dissolved reactive P (DRP), and total P occurred with the surface broadcast treatments, with CF contributing to the greatest loss. Nutrient losses from the subsurface banded treatment reduced N and P in surface water runoff to levels of the control. Subsurface banding of PL reduced concentrations of inorganic N 91%, total N 90%, DRP 86%, and total P 86% in runoff water compared with surface broadcasted PL. These results show that subsurface band–applied PL can greatly reduce the impact of N and P loss to the environment compared with conventional surface-applied PL and CF practices.

Interest in maintaining water quality for environmental sustainability has been a major concern among agricultural researchers and land managers in recent years. This interest is attributed to the belief that agriculture is a major contributor to water quality impairment. Poor fertilization practices, both inorganic and organic, can contribute to water quality degradation through nutrient loss in surface water runoff. These nonpoint source nutrient losses can result in environmental degradation and eutrophication of surface waters. Consequently, research is needed to develop new technologies and better management practices that can be implemented to increase nutrient retention in soil.

Specifically, P has been identified as the most critical nutrient posing a threat for eutrophication of freshwater (USEPA, 1996; Sharpley et al., 1999). Phosphorus is one of the least mobile fertilizer nutrients added to soil, and surface water transport is the primary source for loss from agricultural land (Lemunyon and Daniel, 2002). Phosphorus loss from land to water bodies occurs through dissolved forms (soluble P runoff) attached to particulate matter and eroded sediment, or to a lesser extent by leaching through the soil profile (Lemunyon and Daniel, 2002). It has been reported that an average of only 30% of the fertilizer and feed P input to farming systems is output through crops and animal produce (Sharpley et al., 2003), leaving the excess P susceptible to loss to the environment. Because of these concerns, agricultural practices that improperly or overapply P have been the topic of recent environmental discussion. To abate these environmental concerns related to P loss, considerable effort is being made to develop new technologies and implement management practices that target the amount of P loss from agricultural land.

Similar strategies have been made to reduce N loss to the environment. Unlike P, the major pathway through which N impacts water quality is through groundwater leaching. For instance, N in fertilizer added to soil as NO_3 takes on a dynamic characteristic, enabling vertical movement (leaching) through the soil profile. Consequently, most research has focused on NO_3 exports to gaining streams as influenced by groundwater discharged to water bodies. However, if an intensive rainfall event occurs shortly after fertilization, urea fertilizer or manure (these nutrient sources have to be mineralized) added to agricultural land have the potential for NH_4 loss through surface water transport, before these nutrient sources are mineralized to NO_3.

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Abbreviations: CF, commercial fertilizer; DRP, dissolved reactive phosphorus; PL, poultry litter; TSP, triple superphosphate.

Most of the water quality degradation from agriculture is a result of management and land use. However, evidence indicates that the growing animal industry also accounts for 16% of water quality problems (USEPA, 2001). This has generated increased concerns in areas where animal production is concentrated. For instance, poultry production is significant in the southeastern United States, with Georgia (16%), Arkansas (13%), and Alabama (11%) producing approximately 40% of the nation's 8.9 billion broilers (USDA National Agricultural Statistics Service, 2007), generating 11.4 million tonnes of broiler litter (1.5 kg litter broiler^{-1}) each year (Mitchell and Tu, 2005). Historically, the most common poultry litter (PL) fertilization method has been surface broadcasting in pastures and, to a lesser extent, cropland. Surface broadcasting PL on pastures has been shown to concentrate nutrients at the soil surface, thereby significantly increasing P loss in surface runoff (Gaston et al., 2003; He et al., 2009). This is because most (>75%) of the P in PL is inorganic and 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% is water extractable. Thus, improper land application can be a major threat to surface water, potentially causing eutrophication through soluble-P enrichment of surface waters (Sharpley, 1995; Daniel et al., 1998). Incorporation of manure through tillage has generally been shown to reduce the potential for P loss in runoff (Eghball and Gilley, 1999). Kaiser et al. (2009) reported approximately 88 and 77% reduction in dissolved reactive P (DRP) and total P, respectively, with the use of tillage to incorporate PL. Although research has shown that PL incorporation through tillage can reduce P loss in cropland, this practice is not possible in a pasture system where tillage for incorporation would destroy forage yields.

Subsurface applying manure by injecting slurry in subsurface bands has been shown to reduce N and P losses and increase forage yields (Ross et al., 1979; Baker and Laflen, 1982). However, subsurface band application equipment for dry manure such as PL is not presently available for widespread use. Recently, a four-row prototype implement was developed at the USDA-ARS National Soil Dynamics Laboratory (NSDL) to subsurface band apply PL in soil. Research is needed to evaluate the impact this implement has on reducing nutrient loss in surface water runoff from different soil types and management practices. Thus, the objective of this study was to evaluate the effectiveness of subsurface banding PL compared with the standard surface broadcasting practice in a bermudagrass pasture managed on two different soil types.

Materials and Methods

Experimental Site Description

The study was conducted on a soil type typically found in the Coastal Plain and Piedmont regions of the United States. The Coastal Plain soil type was a Marvyn loamy sand (fine-loamy, kaolinitic, thermic Typic Kanhapludults) located at Auburn University Main Campus Experiment Farm, Auburn, AL. The Marvyn series consists of deep, well-drained, moderately permeable soil with 1 to 6% slopes. The Piedmont soil type was a Hard Labor loamy sand (fine, kaolinitic, thermic Oxyaquic Kanhapludults) located at the Alabama Agricultural Experiment Station, Piedmont Research Unit at Camp Hill, AL. The Hard Labor series consists of very deep, moderately well drained, slowly permeable soils with 2 to 6% slopes.

Rainfall Simulations and Plot Layout

Protocols established by the National Phosphorus Research Project (2001) were used to construct plots and evaluate surface water runoff. A rainfall simulator was used to generate surface water runoff. Rainfall was created using a TeeJet 1/2 HH-SS50WSQ nozzle (Spraying System Co., Wheaton, IL) approximately 2.5 m above the soil surface to achieve terminal velocity of water droplets (Sharpley and Kleinman, 2003). The rainfall simulator's dimensions were 2.5 m long by 2.5 m wide. Simulated rainfall was applied at a rate of approximately 89 mm h^{-1} (corresponds to a 5-yr storm event for the area) to generate runoff for 40 min. Water from the nearby municipality was used as the water source for rainfall simulation. No appreciable amount of N or P was found in the water source. Before rainfall simulations, at each location, the simulator was calibrated to ensure accurate rainfall intensities.

At both the Coastal Plain and Piedmont sites, runoff plots were established on hillslopes in an established bermudagrasss hay pasture (ungrazed) with a uniform slope of approximately 5%, which is representative of the local topography. Each plot was 1.21 m wide and 2.43 m long with the long axis oriented parallel to the flow path. Galvanized metal plot borders extending approximately 13 cm below the soil surface and 7 cm above the soil were installed to keep surface water within the plot. A galvanized metal trough was located on the down-slope end of each plot to collect and transport runoff to a collection point. The plots were mowed before conducting the experiment and vegetation was removed, leaving the grass with a sward height of approximately 15 cm.

Treatments and Sample Analysis

Treatments consisted of surface broadcasted PL at a rate of 9.0 Mg ha^{-1}, subsurface banded PL at a rate of 9.0 Mg ha^{-1} using 38-cm band spacings, surface broadcasted commercial fertilizer (CF; urea and triple superphosphate [TSP] blend) at the equivalent N (330 kg N ha^{-1}) and P (315 kg P ha^{-1}) application rate of the PL, and a nonfertilized control. Surface broadcasted CF and PL was applied by hand. Subsurface banded PL was applied using a tractor-mounted four-row prototype implement developed at the USDA-ARS NSDL (Farm Show Publishing, 2009). For each band, the implement formed a trench in the soil. Poultry litter was applied in the trench, and presswheels were used to backfill soil in on top of the PL. Each PL band extended from 5 to 8 cm beneath the soil surface, allowing the band to be covered with 5 cm of soil (Fig. 1). Subsurface PL bands 4 cm wide were placed in plots perpendicular to the slope.

Rainfall simulations were conducted within minutes of imposing treatments. Soil moisture within each plot was determined just before rainfall simulations in the top 5 cm of soil using a portable soil moisture meter (Th2O probe, Dynamax Inc., Houston, TX). Each runoff event was conducted for a minimum of 40 min. Initiation of runoff was determined when a continuous stream of water ran over the metal trough. Once runoff was initiated, water samples were collected manually at 10-min intervals (0, 10, 20, 30, and 40 min) for the duration of the event to determine temporal changes in N and P over time. Flow rate was determined by recording the time to fill a 250-mL sample bottle at each sampling time. Runoff was pumped from the collection basin and into a fiberglass tank. Upon simulation completion, runoff volume in the tank was measured and cumulative water samples were collected to determine the cumulative nutrient loss concentration of N and P from the runoff event. Source water samples from the simulator were also collected during each simulation to determine background nutrients.

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 by Auburn University Soil Testing Laboratory for soluble P using the inductively coupled argon plasma (Hue and Evans, 1986) and dissolved NO_3–N and NH_4–N concentrations using a Technicon Autoanalyzer 3 (Seal Analytical, Buffalo Grove, IL) with colorimetric methods (Mulvaney, 1996). Total Kjeldahl N and total P were determined on unfiltered runoff water samples. Total Kjeldahl N was determined by steam distillation using procedures described by Bremner (1996) and total P was determined with the microwave digestion procedure (USEPA, 1995) and measured by Ar plasma emission spectrometry (Soltanpour et al., 1982) using the ICAP 9000 (Thermo Jarrell Ash, Franklin, MA). Poultry litter used in this study was analyzed for total N, P, K, Ca, Mg, and micronutrient concentrations using procedures outlined by Hue and Evans (1986). Chemical characteristics of the PL are presented in Table 1. Mass loss (loading) was determined for nutrient concentrations of NO_3–N, NH_4–N, inorganic N (NO_3–N + NH_4–N), total N, DRP, and total P. Loads were calculated by multiplying the nutrient concentration mass loss by the volume of runoff.

Statistical Analysis

The experimental design of this study was a randomized complete block with three replicates. Statistical analysis was performed with analysis of variance techniques using the Proc GLM procedure of SAS (SAS Institute, 1999) to determine treatment effects and their interactions. Means were separated using LSD value; a significance level of $\alpha = 0.10$ was established a priori.

Fig. 1. Bermudagrass pasture after subsurface band application of poultry litter using a four-row prototype banding implement.

Results and Discussion

Time from the start of rainfall simulation to initial runoff was not significantly different between locations or treatments. The average time needed to create surface water runoff was approximately 8 min (8.7 min for Coastal Plain soil and 7.9 min for Piedmont soil). Differences in runoff volume and flow rate were significant ($P < 0.0001$) between locations (Fig. 2). Average runoff volume and flow rate during the runoff event was 137.0 L and 2.7 L min^{-1} for the Coastal Plain soil and 44.0 L and 1.81 L min^{-1} for the Piedmont soil, respectively. Differences in runoff volume and flow rate were most likely caused by differences in water infiltration rate, which was probably influenced by soil moisture. Average volumetric moisture content in the Coastal Plain soil was approximately 21.0%, while volumetric moisture content in the Piedmont soil was 4.1%. Runoff volume and flow rate were significantly impacted ($P = 0.0447$) by treatment only on the Coastal Plain soil (Fig. 3). The primary difference observed was between subsurface banding of PL compared with surface broadcast of PL and CF (urea and TSP blend), resulting in a lower flow rate and runoff volume from subsurface banded PL compared with the other treatments. Although not significant in the Piedmont soil, subsurface banding of PL also had the lowest runoff volume and flow rate.

Cumulative Nitrogen Runoff Concentrations

Nitrogen loss in surface water runoff was distinctly impacted by the fertility application method (surface broadcast vs. subsurface banding) for both locations. Visual differences

Table 1. Poultry litter and soil chemical (Mehlich 1, except for pH, C, and N) characteristics on a dry-weight basis.

Parameter	Depth	pH	C	N	P	K	Ca	Mg	Al	B	Cu	Fe	Mn	Zn
	cm		$g\ kg^{-1}$						$mg\ kg^{-1}$					
Poultry litter			344.00	40.40	20.60	42.10	32.70	11.0	1438	65	643	3199	596	620
Soil														
Coastal Plain	0–5	6.46	24.17	1.52	0.018	0.013	0.63	0.63	579	2.0	1.0	58	18	6.3
	5–10	6.59	7.52	0.59	0.008	0.003	0.24	0.21	606	2.6	1.9	58	8.2	2.3
Piedmont	0–5	6.84	17.13	1.07	0.016	0.066	0.79	0.90	621	0.1	0.9	6.6	34	1.6
	5–10	6.76	8.03	0.55	0.007	0.002	0.40	0.63	597	2.8	1.2	9.5	22	1.1

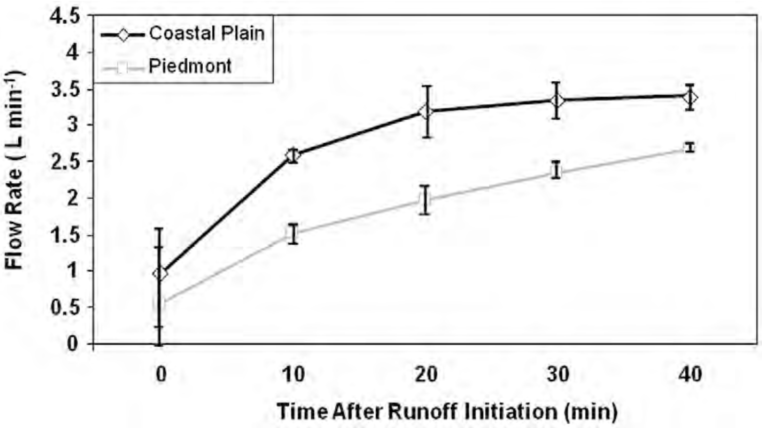

Fig. 2. Mean flow rate of the runoff water at 10-min intervals during the rainfall simulation event for the Coastal Plain and Piedmont soils.

between treatment impacts are shown in Fig. 4. Nitrogen losses tended to be higher from the Piedmont soil compared with the Coastal Plain (Fig. 5). Mean nutrient loss of NH_4–N, which is a portion of the inorganic N fraction, was significantly affected by treatment ($P < 0.0001$, Coastal Plain; $P = 0.0294$, Piedmont). Ammonium loss in surface water runoff was significantly higher for the surface broadcast PL and urea treatments compared with control and subsurface banded PL treatments at both locations. Subsurface banding of PL was so effective at reducing NH_4–N losses in runoff water that NH_4–N levels observed in the banded treatment were similar to those observed in the control. In the Coastal Plain soil, higher NH_4–N loss ($P = 0.0362$) was observed in the surface broadcasted PL treatments, while higher NH_4–N were observed in surface broadcasted urea treatments for the Piedmont. This was attributed to the Coastal Plain soil having a lower infiltration rate, which increased runoff volume from the plot. As a result of an increased runoff volume, within minutes after fertilization, some dissolved urea was probably transported off the plot with surface water runoff before hydrolyzation occurred to transform the urea to NH_4.

Similar to NH_4–N, NO_3–N loss was affected by the fertility application method (Fig. 5). However, this was only significantly observed in the Piedmont soil ($P = 0.0474$). The practice of subsurface banding PL significantly reduced NO_3–N losses to levels that were similar to the control, while NO_3–N losses for surface broadcast application of PL and urea were significantly higher for the Piedmont soil. This suggests that subsurface band application of PL provides better protection from NO_3 loss in runoff compared with surface broadcast application. Although no significant differences were observed between surface application of PL and urea, the highest overall NO_3–N loss was observed in the urea treatment. This suggests that the urea treatment converted N to NO_3 faster than the PL and thus has a greater potential for NO_3 loss directly after application compared with PL. Under conditions where N fertilizers are applied a day or two before a runoff event, NO_3 would have moved into deeper soil depths as a result of its dynamic characteristics (leaching ability). However, in this study the fertility treatments were applied minutes before initiation of rainfall simulations, thus leaving the NO_3 from the N source susceptible to loss in runoff.

Higher NH_4–N losses ($P < 0.0001$) were observed in surface runoff compared with NO_3–N at both locations (Fig. 5). These results were not unexpected because normally the N in PL and urea have to be transformed to a plant-available form by microbial activity following soil contact. The result suggests that some hydrolysis (urea) and mineralization (PL) had occurred, but nitrification had not occurred before the rainfall

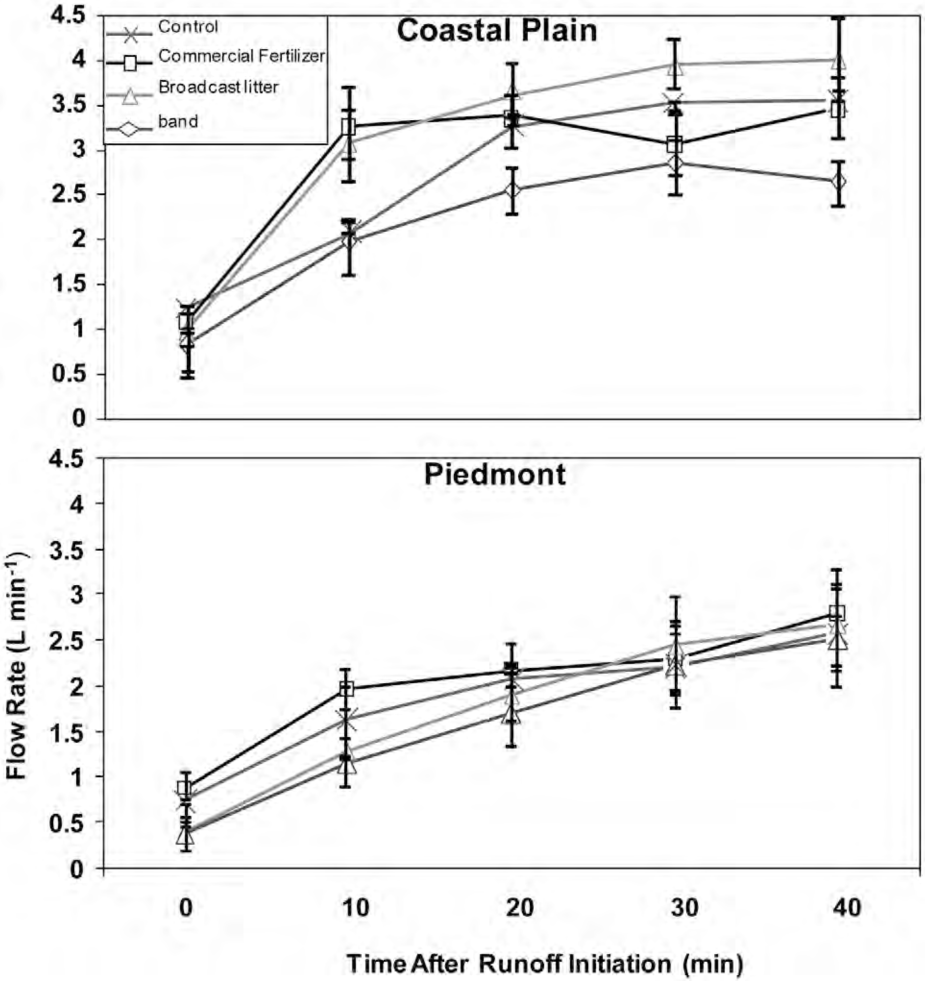

Fig. 3. Mean flow rate of the runoff water at 10-min intervals between treatments during the rainfall simulation event for the Coastal Plain and Piedmont soils.

simulation. For instance, urea is highly soluble in water and once it comes in contact with a moist soil surface it is rapidly hydrolyzed by enzymes to NH_4 or NH_3. This ammonium or ammonia is then oxidized by bacteria to NO_3 (Sharpley et al., 1983). Environmental conditions such as moisture and temperature impact the rate at which NH_4 from urea is nitrified into NO_3. Poultry litter also goes through a mineralization followed by nitrification process similar to urea except at a slower rate. Rainfall simulations occurred minutes after application of the N source, so it is not surprising that NH_4 is the dominant form of N.

Inorganic N (NO_3–N + NH_4–N) loss in runoff followed the same trend as observed for NH_4–N (Fig. 5). This was expected because NH_4–N was the predominant form of N loss in runoff and accounted for >75% of the inorganic N. Inorganic N losses from surface broadcast of urea and PL were 10 to 13 (Coastal Plain soil) and 24 to 29 times (Piedmont) those of the control, while the subsurface banded PL treatment was only two times those of control. A 91% reduction in inorganic N loss to surface water runoff was achieved by subsurface banding PL compared with surface broadcasting the PL. Differences in N loss observed between subsurface banding of PL compared with broadcasting urea and PL suggests that surface application practices are more susceptible to nutrient loss. However, burying PL in subsurface bands, 5 cm below the soil surface, largely protected the nutrients from loss in surface water runoff.

To fully determine the impact fertility treatments and method of application has on surface water runoff, a complete understanding of N export is needed. An evaluation of total N loss in surface water runoff can help provide a better understanding of how fertility treatments and method of application can affect N transport. Higher losses of total N in runoff water ($P < 0.0001$) were observed in the Piedmont soil compared with the Coastal Plain soil (Fig. 6). This was most likely attributed to runoff volume affecting N concentrations in runoff. Higher runoff volume and flow rate observed in the Coastal Plain soil probably resulted in a dilution of the total N lost during the runoff event. Broadcast application of urea and PL significantly impacted the amount of total N lost during the runoff event at each location. Total N loss was in the order of surface broadcast urea > surface broadcast PL > subsurface banded PL = control. Similar to the observed differences with inorganic N loss, subsurface banding of PL reduced total N loss to control levels. A comparison between the surface broadcast and the subsurface banded PL treatment showed that subsurface banding PL reduced total N approximately 90% compared with the surface broadcast treatment. These trends were observed for soil at both locations. This helps explain the observed differences stated above between locations (Coastal Plain vs. Piedmont) for the surface broadcast–applied urea and PL. Previously, it was noted that higher inorganic N loss was observed when PL was surface broadcast applied compared with urea in the Coastal Plain soil. When evaluating the Piedmont soil, the opposite was observed with surface broadcast–applied urea losing more N than surface broadcast–applied PL. However, total N was higher for the surface broadcast–applied urea compare to PL in both soils. This suggests that some of the urea that was lost during the runoff event in the Coastal Plain soil had not transformed into NH_4 or NO_3 before surface runoff. Thus, some of the N was probably transported in the urea form off the plot with surface water runoff.

Fig. 4. Cumulative treatment impacts on clarity of runoff water from the rainfall simulation event.

Temporal Inorganic Nitrogen Runoff Concentrations

An evaluation of surface water runoff at different time intervals during the rainfall simulation is critical to understanding how nutrient loss changes over time. Inorganic N (NH_4–N + NO_3–N) runoff concentrations collected at each time interval during the rainfall simulation are presented in Fig. 7. Mean inorganic N loss for surface broadcasted urea and PL treatments were the greatest shortly after runoff began and decreased over time. The observed loss at the beginning of the runoff event accounted for the majority of the total inorganic

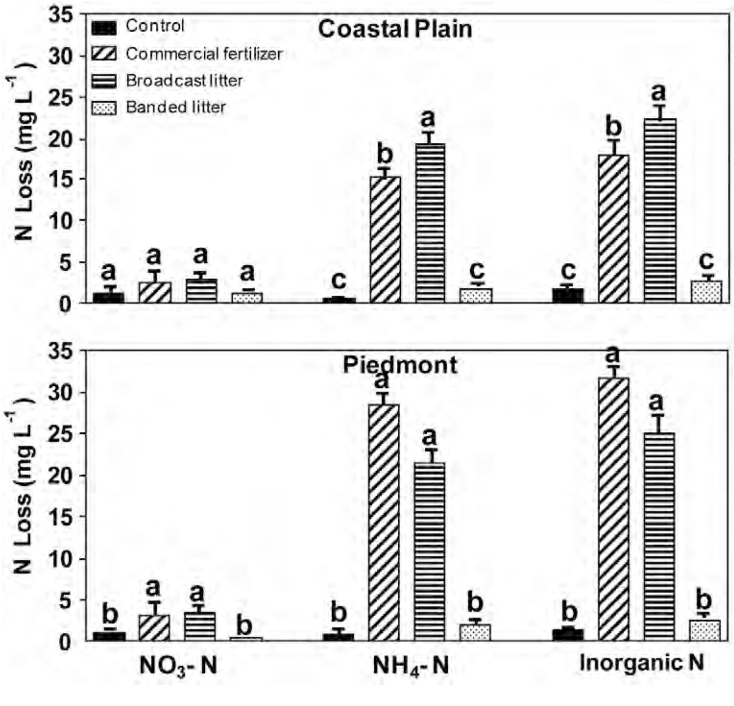

Fig. 5. Mean cumulative nitrate (NO_3–N), ammonium (NH_4–N), and inorganic N (NO_3–N + NH_4–N) concentration loss in runoff water between treatments during the rainfall simulation events for the Coastal Plain and Piedmont soils. Within each nutrient, bars with the same letter are not significantly different ($\alpha = 0.10$).

N concentration loss from the surface broadcasted PL and urea treatments. Declines in inorganic N loss observed throughout the runoff event likely resulted from the amount of inorganic N on the soil surface decreasing with time during the rainfall event, as runoff water transported N off the plot. Further explanation is that the inorganic N concentration became diluted over time. This corresponds with the increase in flow rate observed throughout the rainfall event. Thus, as flow rate increased, the amount of water in runoff increased for the given time interval, therefore diluting nutrient concentrations in the runoff water. Previous research has also attributed temporal declining nutrient concentrations in runoff water to dilution, resulting from increasing flow over time during the runoff event (e.g., Vadas et al., 2004; Kleinman et al., 2006).

Unlike the surface application of urea and PL, mean inorganic N losses were relatively low for subsurface banded PL throughout the entire runoff event. Inorganic N losses in runoff for the subsurface banded PL treatment remained below both the USEPA 10 mg L^{-1} drinking water standard for NO_3 (USEPA, 2006) and the aquatic water quality ammonia criterion of 5.0 mg N L^{-1} (USEPA, 2009) throughout the entire runoff event compared with the surface broadcasted treatments. Visual differences observed for temporal changes in water clarity over time for subsurface application and surface broadcast PL are shown in Fig. 8.

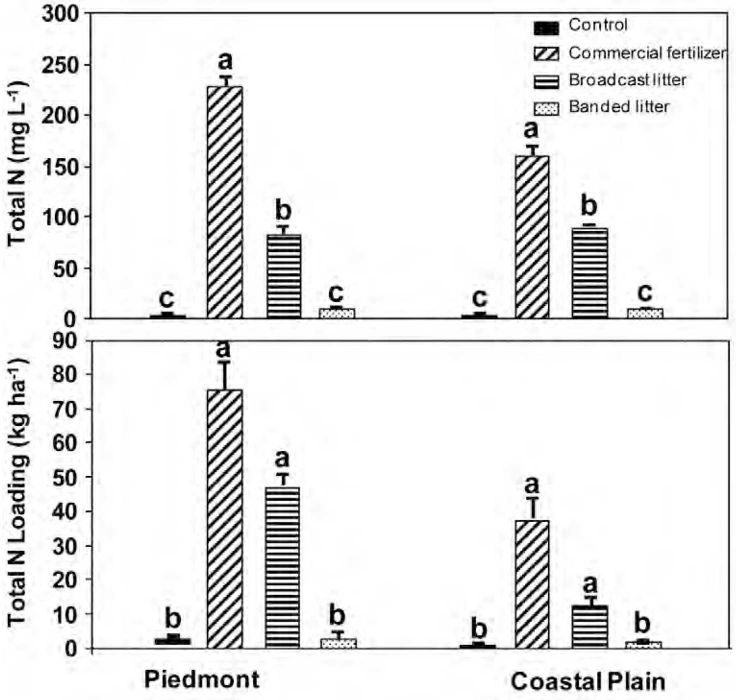

Fig. 6. Mean cumulative total nitrogen (N) concentration loss and loading in runoff water between treatments during the rainfall simulation event for the Coastal Plain and Piedmont soils. Within each nutrient, bars with the same letter are not significantly different (α = 0.10).

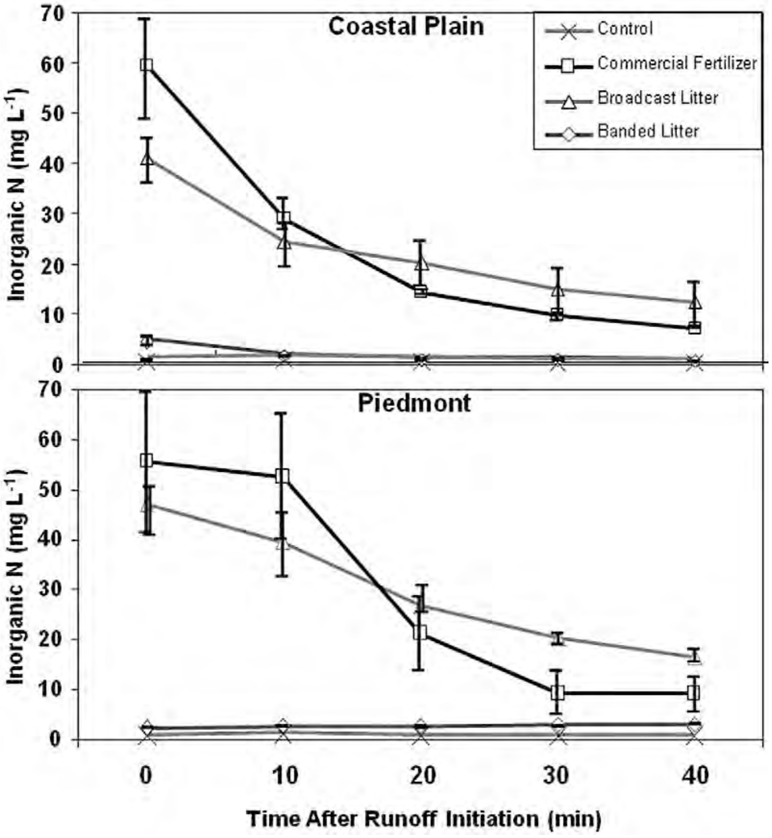

Fig. 7. Mean inorganic N (NO_3–N + NH_4–N) concentration loss in runoff water at 10-min intervals between treatments during the rainfall simulation event for the Coastal Plain and Piedmont soils.

Cumulative Phosphorus Runoff Concentrations

Subsurface banding PL had a distinct impact on the P loss in surface water runoff, significantly decreasing DRP losses compared with surface application of PL. Mean DRP losses as affected by fertility application and method are shown in Fig. 9. Surface broadcasted PL and TSP increased DRP in surface water runoff, relative to subsurface banded PL and control, at both locations. Dissolved reactive P loss in runoff was significantly greater when TSP was surface broadcast applied compared with PL surface broadcast. This was most likely attributed to the TSP being more soluble than the PL. These results suggest that CFs have a greater potential for P loss compared with organic fertilizer sources. However, when PL was applied in subsurface bands, P losses were greatly reduced to control levels. A comparison between surface broadcast PL and subsurface banded PL showed that an 86% reduction in DRP can be achieved by subsurface banded PL compared with surface broadcast. These results indicate that subsurface banding PL beneath the soil 2 cm will drastically reduce the potential and magnitude for P loss in surface water runoff. Consequently, subsurface placement of PL in soil protects the litter from surface water contact, allowing the P to remain in the soil. On the other hand, surface applying PL or TSP shortly before a rainfall event has the potential for P loss, which could contribute to water quality degradation.

Differences in total P loss were similar to trends observed for DRP losses. This was probably a result of similar conditions between total P and DRP influencing nutrient loss in surface water runoff. Also, differences between total P and DRP were minimal, suggesting that DRP was the dominant form of P loss from the plots. Dissolved reactive P averaged 93 and 82% of the total P loss for the surface broadcast applied TSP and PL, respectively. Total P in surface water runoff is comprised of DRP in water, sediment-bound P, organic P in sediment, and dissolved organic P. In this study, differences between the total P and DRP were relatively low, suggesting that there was a minor P contribution from sediment loss. Essentially, most of the P loss from the bermudagrass pasture was in a dissolved reactive form with minor contribution from organic and sediment P loss.

It was not surprising that most of the P loss was DRP because, in pastures, a thick thatch layer will act as a filter, restricting the movement of soil particles associated with runoff water. Thus, primarily soluble forms of P are lost in a managed pasture system. This is similar to findings of Torbert et al. (2005), who observed primarily DRP in surface water runoff from a bermudagrass pasture fertilized with turkey litter. Torbert et al. (2005) also measured particulate matter loss in runoff and found no measurable amount of sediment loss, thus suggesting that most of the P loss was in the form of DRP.

Surface broadcast application of TSP and PL significantly increased total P loss, while subsurface banding of PL was similar to control levels. Subsurface banding PL reduced total P loss by 86% compared with surface broadcasting PL. Clearly, results from this study show that surface application of a high-P fertilizer source has a greater transport potential which can be controlled by subsurface band application. Differences were observed between surface broadcast application of TSP and PL, with TSP contributing the greatest losses.

Although total P loss from surface broadcasted PL was less than that of TSP, the same amount of P was applied for both the PL and TSP treatments. These differences suggest that there are differing susceptibilities for P transport in runoff between these two sources. For instance, TSP as well as other CFs, have a higher solubility than PL. Poultry litter is a dry material and during a rainfall event the litter has to be saturated for nutrients to dissolve. In addition, litter clumps must be physically broken down before DRP and total P are released into surface water runoff (Vadas et al., 2004).

Temporal Dissolved Reactive Phosphorus Runoff Concentrations

Mean DRP loss, as affected by the fertility treatments and method of application, observed during the runoff event for each sampling time is presented in Fig. 10. A significant interaction between treatments and time were observed ($P < 0.0001$, both locations); this was attributed to surface broadcasted PL and TSP DRP loss changing over time, while the control and subsurface banded PL remained constant throughout the runoff event. The highest loss of DRP was observed during the first few minutes of the runoff event and decreased over time. This suggests that the most concentrated nutrients are lost during the first few min-

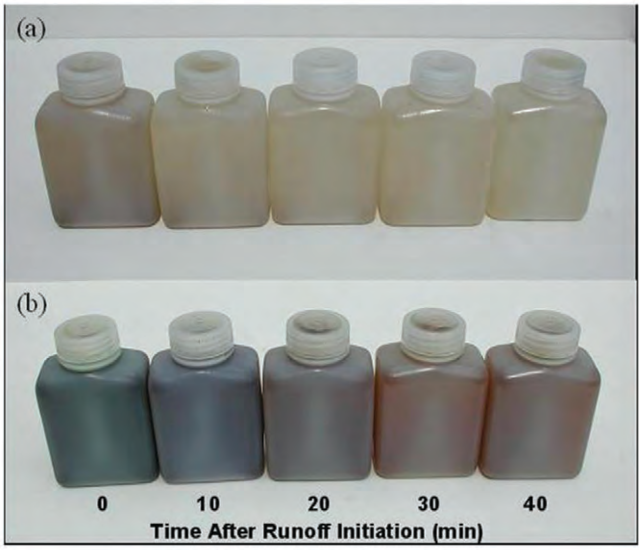

Fig. 8. Temporal changes in water clarity at 10-min intervals during the rainfall simulation event for (a) subsurface banded litter and (b) surface broadcast litter.

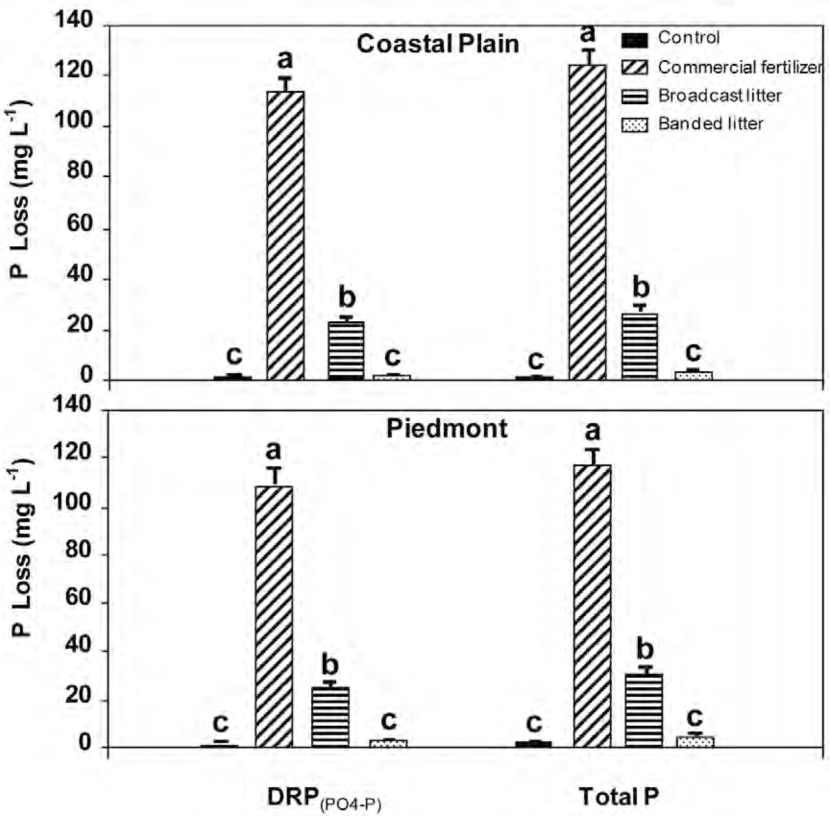

Fig. 9. Mean cumulative dissolved reactive phosphorus (DRP) and total P concentration loss in runoff water between treatments during the rainfall event for the Coastal Plain and Piedmont soils. Within each nutrient, bars with the same letter are not significantly different ($\alpha = 0.10$).

utes of a runoff event. Similar to the temporal changes observed for the inorganic N, DRP loss with the banded treatment was low at the start of the runoff event and remained low throughout the runoff event similar to the control. The greatest runoff loss observed within each time interval throughout the entire 40-min runoff event was in the TSP treatment. This was probably a result of the TSP having a higher solubility of P compared with PL. Vadas et al. (2004) evaluated surface water runoff from soil fertilized with PL and reported that physical breakdown of litter clumps had to occur to release DRP during a runoff event. Unlike organic fertilizer sources such as PL, the DRP in the TSP (inorganic P fertilizer) is in a more soluble and readily available form. Results from the temporal change in DRP loss over time suggest that subsurface banding PL would be effective even in short-duration runoff events and therefore would be a great solution for reducing the impact P loss has on eutrophication of streams and lakes.

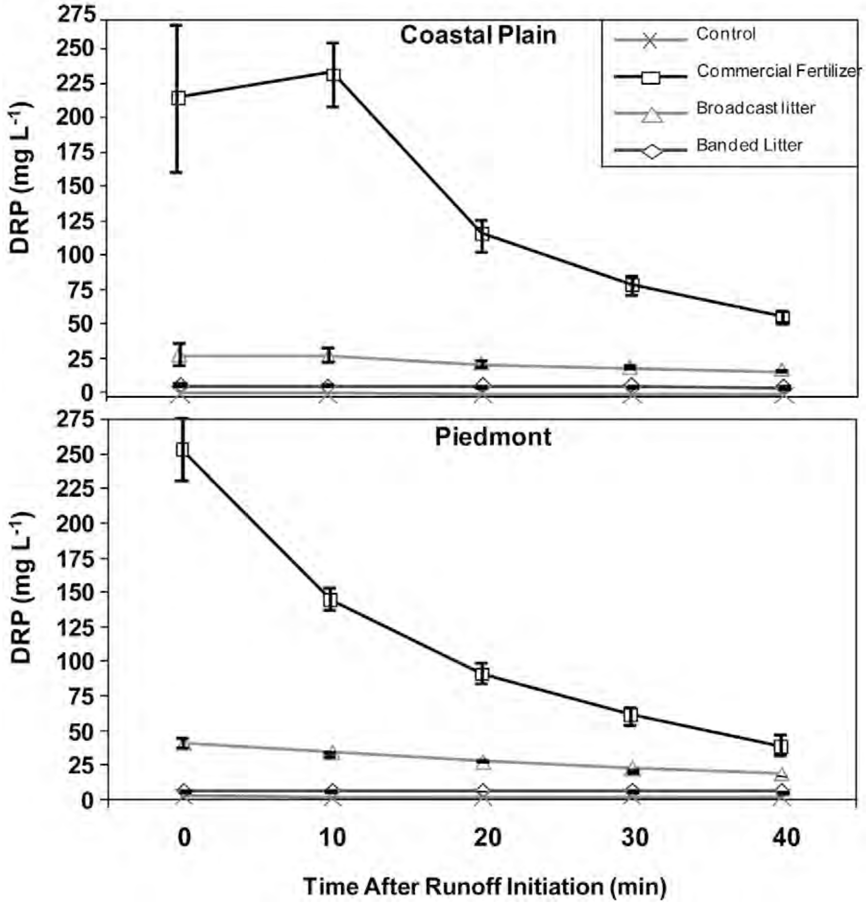

Fig. 10. Mean dissolved reactive phosphorus (DRP) concentration loss in runoff water at 10-min intervals between treatments during the rainfall simulation events for the Coastal Plain and Piedmont soils ($\alpha = 0.10$).

Mass Loss of Nitrogen and Phosphorus Runoff

In general, trends observed in nutrient loading from the runoff water were similar to trends in runoff concentration losses for the different treatments. Significant differences in loading ($P = 0.0148$) were observed between the two soils (Fig. 11 and 12). For both N and P, the Coastal Plain soil had a higher loading compared with the Piedmont soil. Loading is a product of the runoff volume and nutrient concentration in the runoff water. In this case, differences in loading were primarily attributed to differences in runoff volume between the two locations. Similar to NO_3–N, NH_4–N, inorganic N, total N, DRP, and total P concentration losses, significantly greater nutrient loads were observed for surface broadcasted PL, urea, and TSP compared with subsurface banded PL in general. It is also important to note that subsurface banding of PL had similar loading compared with control. Clearly this study shows that subsurface banding of PL has the potential to significantly reduce the amount of dissolved and total nutrients reaching surface water bodies. In addition, a reduction of dissolved nutrients from agricultural land could have a substantially positive impact on the environment. For instance, a reduction of dissolved nutrients reaching water bodies could help prevent eutrophication because dissolved nutrients are available for immediate biological uptake in these water bodies (Sharpley et al., 1991, 1992; Torbert et al., 2005). Research has shown that manure application below the soil surface reduces nutrient loss in runoff (Ross et al., 1979; Baker and Laflen, 1982; Eghball and Gilley, 1999; Pote et al., 2003; Torbert et. al.,

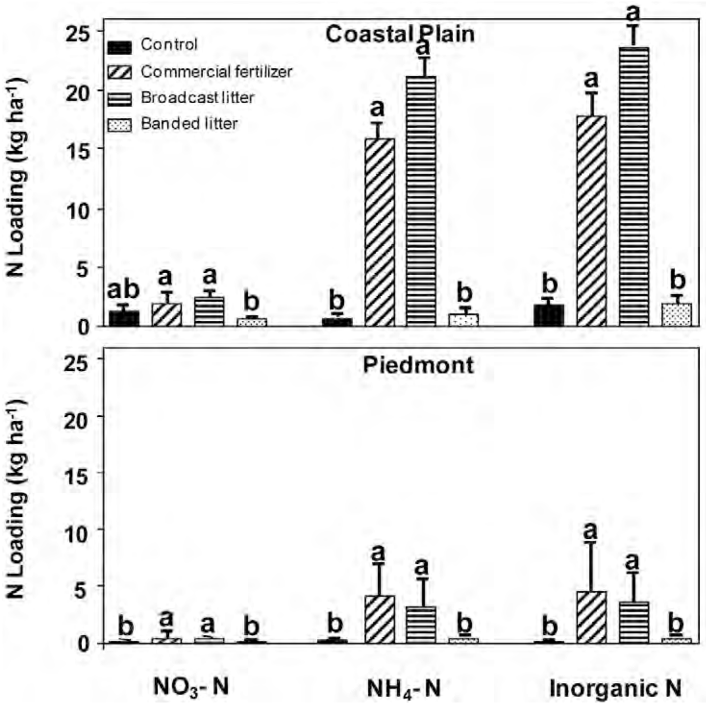

Fig. 11. Mean cumulative nitrate (NO_3–N), ammonium (NH_4–N), and inorganic N (NO_3–N + NH_4–N) loading loss in runoff water between treatments during the rainfall simulation event for the Coastal Plain and Piedmont soils. Within each nutrient, bars with the same letter are not significantly different ($\alpha = 0.10$).

2005). For example, liquid manure injection has been shown to be very effective at reducing N and P loss in runoff (Ross et al., 1979; Baker and Laflen, 1982). Subsurface banding of PL using a one-row experimental implement has also been shown to reduce nutrient losses (N and P) in a tall fescue (*Festuca arundinacea* Schreb.) pasture applied 1 d before rainfall simulations (Sistani et. al., 2009). In this current study, using a four-row prototype implement to subsurface band PL, a clear reduction in NH_4–N, total inorganic N, total N, DRP, and total P loss was achieved in surface water runoff from a bermudagrass pasture fertilized just minutes before rainfall simulation occurred. This indicates that under the worst conditions, where a high-intensity rainfall event creates surface water runoff shortly after fertilization, subsurface banding of PL will be very effective at reducing nutrient loss to the environment.

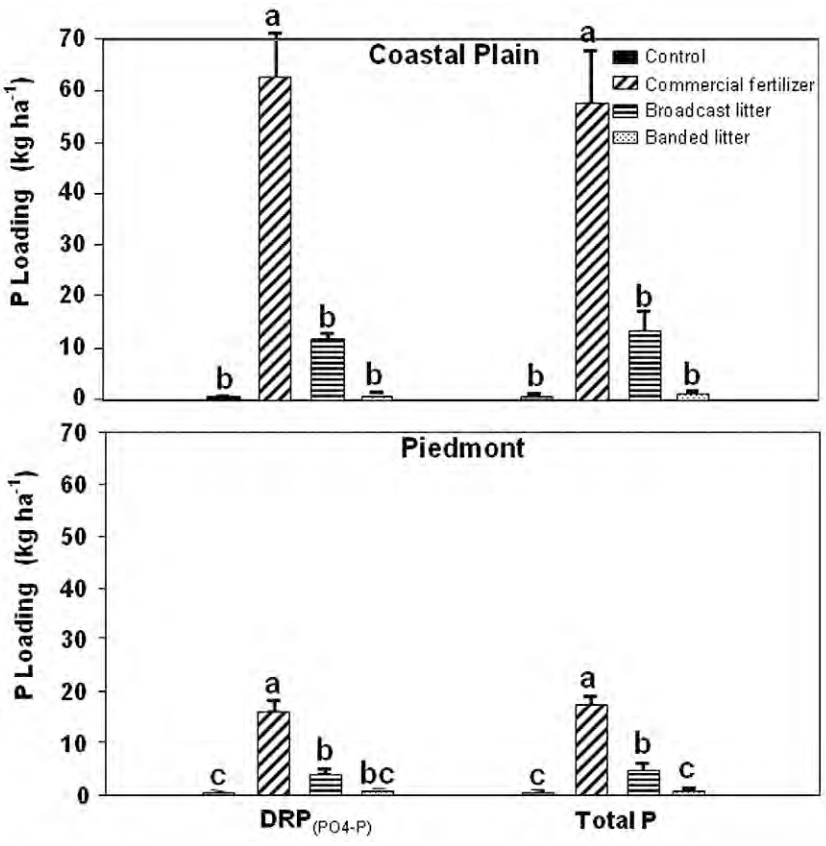

Fig. 12. Mean cumulative dissolved reactive phosphorus (DRP) and total P loading loss in runoff water between treatments during the rainfall simulation event for the Coastal Plain and Piedmont soils. Within each nutrient, bars with the same letter are not significantly different ($\alpha = 0.10$).

Conclusions

Nitrogen and P are two of the most important fertilizer nutrients needed for agricultural production. However, improper fertilization practices using these nutrients can be a detriment to the environment by contributing to surface water eutrophication. This study demonstrated that the fertilizer application method used (surface broadcast vs. subsurface banding) can impact nutrient loss to the environment. Surface broadcast application of CF and PL resulted in the greatest N and P loss, with CF being the greatest contributor. However, nutrient loss in surface water runoff was greatly reduced by subsurface applying PL in shallow bands below the soil surface. Higher nutrient concentration losses were observed in the Piedmont soil compared with the Coastal Plain soil. On the other hand, the greatest nutrient loading losses were observed in the Coastal Plain soil. This was primarily attributed to the changes in runoff volume. A lower runoff volume resulted in a more concentrated nutrient loss in the Piedmont soil, while higher runoff contributed to increased loading in the Coastal Plain soil. Temporal changes in runoff during the course of the rainfall simulation showed that nutrient concentrations in runoff water were greatest during the first few minutes after runoff began and decreased over time. This study specifically evaluated the impact of a "worst-case scenario," an intensive rainfall event shortly after fertilizer application. Under these conditions, subsurface banding of PL will dramatically reduce N and P losses in surface water runoff.

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