Broiler Litter Application Method and Runoff Timing Effects on Nutrient and *Escherichia coli* Losses from Tall Fescue Pasture

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The inability to incorporate manure into permanent pasture leads to the concentration of nutrients near the soil surface with the potential to be transported off site by runoff water. In this study, we used rainfall simulations to examine the effect of broiler chicken (*Gallus gallus domesticus*) litter application method and the runoff timing on nutrient and *E. coli* losses from tall fescue (*Festuca arundinacea* Schreb.) pasture on a Hartsells sandy loam soil (fine-loamy, siliceous, subactive, thermic Typic Hapludults)) in Crossville, AL. Treatments included two methods of litter application (surface broadcast and subsurface banding), commercial fertilizer, and control. Litter was applied at a rate of 8.97 Mg ha^{-1}. Treatments were assigned to 48 plots with four blocks (12 plots each) arranged in a randomized complete block design to include three replications in each block. Simulated rainfall was applied to treatments as follows: Day 1, block 1 (runoff 1); Day 8, block 2 (runoff 2); Day 15, block 3 (runoff 3); and Day 22, block 4 (runoff 4). Total phosphorus (TP), inorganic N, and *Escherichia coli* concentrations in runoff from broadcast litter application were all significantly greater than from subsurface litter banding. The TP losses from broadcast litter applications averaged 6.8 times greater than those from subsurface litter applications. About 81% of the runoff TP was in the form of dissolved reactive phosphorus (DRP) for both litter-application methods. The average losses of NO_3–N and total suspended solids (TSS) from subsurface banding plots were 160 g ha^{-1} and 22 kg ha^{-1} compared to 445 g ha^{-1} and 69 kg ha^{-1} for the broadcast method, respectively. Increasing the time between litter application and the first runoff event helped decrease nutrient and *E. coli* losses from surface broadcast litter, but those losses generally remained significantly greater than controls and subsurface banded, regardless of runoff timing. This study shows that subsurface litter banding into perennial grassland can substantially reduce nutrient and pathogen losses in runoff compared to the traditional surface-broadcast practice.

Nonpoint-source pollution of water bodies during the past 20 yr has received global attention (Abu-Zreig et al., 2003; Gaston et al., 2003; Sistani et al., 2003). Runoff from agricultural land, particularly manured land is a major nonpoint source of nutrients, pathogenic microorganisms, and eroded sediment (Hansen et al., 2002; Tabbara, 2003; Saini et al., 2003; Little et al., 2005). Phosphorus loss from agriculture is a particularly challenging environmental issue because P is a major contributor to water quality problems (Carpenter et al., 1998). Phosphorus-enriched surface water may become eutrophic, leading to increased aquatic vegetation growth and an increase in biological oxygen demand (BOD) (Sharpley et al., 1994; Parry, 1998; Carpenter et al., 1998). In addition, contamination of surface waters by fecal-borne microorganisms can result in serious human health problems, including death (Bicudo and Goyal, 2003).

Proper land application of animal manure is critical to water quality in watersheds with significant risk for transport of nutrients or microbial pathogens to surface water. The risk depends on interactions of intrinsic site properties, climate, and pasture management (Gessel et al., 2004). With regard to permanent pasture systems, inability to incorporate fertilizer amendments leads to increased nutrient concentration, such as P, Cu, and Zn near the soil surface (Little et al., 2005). Substantial P movement from these soils can potentially occur via (a) runoff water at the field edge (Sharpley et al., 1994), (b) leaching through the soil (Heckrath et al., 1995), or (c) lateral transport of dissolved P within the soil (Walthall and Nolfe, 1998). Parameters that vary temporally and/or spatially (such as precipitation, soil type, and soil surface hydrology) also influence P loss at the watershed scale (Gburek et al., 2002). For example, Kleinman and Sharpley (2003) reported that differential erosion of surface broadcast manure between different soil types caused significant differences in runoff total P concentrations. Manure application timing, particularly the time interval between application and the runoff event, greatly impacts the magnitude of observed nutrient losses (Sharpley, 1997). Edwards and Daniel (1993) and Schroeder et al. (2004) reported that potential for P loss peaks when runoff occurs immediately following manure broadcast and then declines over time. In a simulated rainfall study,

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Abbreviations: DRP, dissolved reactive phosphorus; ICP, inductively coupled plasma spectrophotometer; TSS, total suspended solids; TP, total phosphorus.

Edwards et al. (2000) showed that P loss magnitude was also related to the time interval between the preceding rainfall and runoff initiation. Similarly, Pote et al. (1996 and 1999) and McDowell and Sharpley (2002) reported that antecedent soil moisture affects runoff P transport.

More than two-thirds of the total U.S. broiler chicken production is located in the southeastern United States, and is a major segment of the farm economy in the region (USDA Economic Research Service, 2004). Poultry litter (poultry manure mixed with bedding material) is generally used to supply plant nutrients, particularly N and P, to perennial pastures and hay fields. Surface broadcasting is currently the common method for applying poultry litter on perennial forages, but this application method concentrates nutrients and pathogenic microorganisms at the soil surface where they are readily available to runoff water (Doran and Linn, 1979; Coyne et al., 1995; Eghball and Gilley, 1999; Edwards et al., 2000; Dou et al., 2001; Soupir et al., 2006). Increasing P levels at the soil surface are especially common in soils receiving long-term surface applications of poultry litter (Kingery et al., 1994). Thus, the surface broadcast method greatly increases the risk of nutrient losses in surface runoff from fields receiving poultry litter (Pote et al., 2003; Zhao et al., 2001).

Incorporating manure into the soil has been found to decrease nutrient losses in tilled cropping systems. Ross et al. (1979) reported that N and P losses in runoff were almost completely eliminated when dairy manure was injected into the soil. Likewise, Torbert et al. (2005) reported a clear reduction of NH_4–N and PO_4–P loads in runoff from poultry litter applied to cultivated land, indicating that incorporation would be a very effective way to reduce runoff nutrient losses from heavy clay soil. Giddens and Rao (1975) found that incorporation of poultry litter into the top 10 cm of soil reduced NH_3–N volatilization by 55% and doubled the NO_3–N concentration in the soil. While incorporation of litter into soil minimizes nutrient losses in tilled systems, it has not been practical for perennial forage systems (Pote et al., 2003) because conventional tillage incorporation would destroy the grass, requiring the pasture to be reestablished. However, the experimental equipment under study in this project may allow incorporation of litter in a perennial grass system with minimum damage to the forage.

There is currently a need for scientific information regarding the effectiveness of management practices such as poultry litter application method and timing for decreasing transport of nutrients and fecal organisms in runoff, particularly from tall fescue pastures. Therefore, the objectives of this study were (i) to compare the effect of broiler litter application methods (surface broadcast vs. subsurface banding) on nutrient and *E. coli* losses in runoff, and (ii) to determine the impact of time between litter application and the first runoff event on nutrient and *E. coli* losses from tall fescue pasture in the Appalachian Plateau.

Materials and Methods

Site Description and Experimental Design

Runoff plots were constructed on Hartsells fine sandy loam soil at the Alabama Agricultural Experiment Station Sand Mountain Research and Extension Center, Crossville, AL. Plots were constructed on a site with permanent ‘Kentucky 31’ tall fescue pasture. The tall fescue was clipped to approximately 10 cm and the clipped vegetation removed. Protocols established by the National Phosphorus Research Project (2001) were used to construct plots and perform rainfall simulation (except where noted). Each plot was 1.5 m wide and 2.4 m long and approximately 4% slope, with the long axis oriented parallel to the slope. Galvanized metal plot borders extended approximately 13 cm 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. Before initiating runoff, the metal troughs were sterilized with 70% ethanol followed by rinsing with sterilized distilled water.

Two different broiler litter application methods were compared, with broiler litter being applied at a rate of 8.97 Mg ha^{-1} by either broadcast application or by subsurface banding. For the subsurface banding treatment, a tractor-mounted experimental poultry litter applicator device was used to apply the litter in shallow trenches (approximately 5 cm depth and 4 cm width). As the applicator device ran, the single pass of the trencher component formed the full 4 cm width of the trench and the trencher held the trench open while the device deposited litter in the trench. These trenches extended across the width of the plot and were spaced at 38-cm intervals down the slope, for a total of six trenches per plot. Litter filled the bottom 2 cm of each trench, and the applicator device moved soil back over the top of the litter band, filling the top of the trench. Thus, following application, soil above the litter band extended from the surface down to the 3 cm depth, and the litter band extended from 3 to 5 cm beneath the soil surface (Fig. 1). Additional treatments included a broadcast application of commercial fertilizer and a control treatment that received no nutrient additions. The 8.97 Mg ha^{-1} litter rate provided 296 kg N ha^{-1}, 433 kg K ha^{-1}, and 234 kg P ha^{-1}. The commercial fertilizer (19–19–19), formulated from ammonium nitrate, ammonium sulfate, muriate of potash, and triple super phosphate, was applied at a rate of 296 kg N ha^{-1} to equal the N rate applied in the broiler litter treatment, which also provided 246 kg K ha^{-1} and 129 kg P ha^{-1}. Treatments were assigned to plots in a randomized block design with three replications.

To examine the impact of time interval between litter application and the first runoff event, four blocks of plots (12 plots per block) were established. Litter and fertilizer treatments were applied to all plots on the first day of the experiment (16 May 2006). Beginning on 17 May, simulated rainfall was applied to a different block to generate runoff on each of the following days after litter and fertilizer applications: Day 1, block 1 (runoff 1); Day 8, block 2 (runoff 2); Day 15, block 3 (runoff 3); and Day 22, block 4 (runoff 4). Plots were not covered between rainfall simulations, but only one natural rainfall event (6.6 mm) occurred during the study (3 June) and it did not generate any runoff. Simulated rainfall was applied at approximately 110 mm h^{-1} (corresponds to 10-yr storm event for the region) to generate runoff for 30 min from each plot, with a 500-mL water sample collected at each 5-min interval during the runoff event. Flow

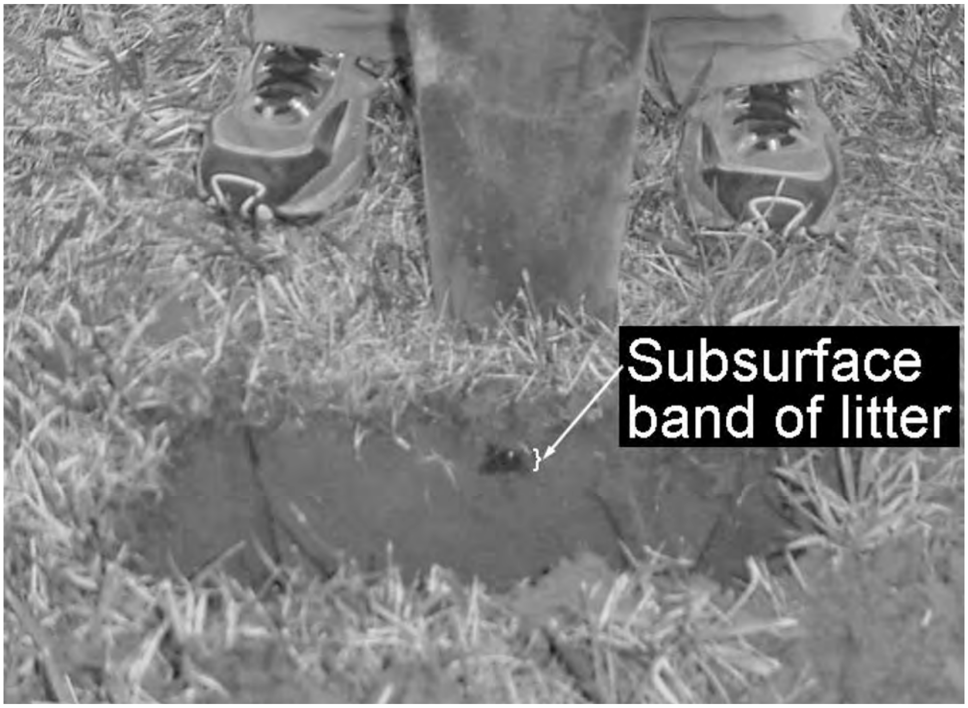

Fig. 1. Small soil profile showing cross-section of a subsurface litter band relative to the soil surface 7 mo after application.

rate was estimated by recording the time to fill a 500-mL sample bottle at each sampling time. All of the runoff water was pumped from the collection basin to a storage tank. Upon completion of the rain simulation, total runoff volume in the tank was measured and a cumulative water sample was collected. Samples of the source water used in the rainfall simulations (local well water) were also collected for chemical and bacterial analysis.

Sampling and Data Analysis

Broiler litter (a mixture of manure and bedding materials) used in this study was collected from local broiler production facilities. A microwave procedure was used to digest litter samples for determination of total nutrient content. Using this method, 0.5 g of litter was mixed with 9 mL HNO_3 and 3 mL HCl in a Teflon microwave digestion vessel, allowed to predigest under a vent hood for 45 min, and then placed in a Mars 5 Microwave (CEM Corp., Matthews, NC). Temperature of the mixture was increased to 175°C in 6.5 min, and held at that temperature for an additional 12 min to complete the digestion process. Samples were then filtered through a Whatman 42 filter (Whatman Chemical Separation, Inc., Clifton, NJ), followed by nutrient determination using a Varian Vista-Pro inductively coupled plasma spectrophotometer (ICP) (Walnut Creek, CA). The pH of the litter was measured in a 1:5 litter/water mixture. Total N and C contents of litter and soil samples were determined using a Vario Max CN analyzer (Elementar Americans, Inc. Mt. Laurel, N.J.).

All the runoff water samples collected were digested using the microwave procedure before being analyzed by ICP to determine TP. Total suspended solids concentration was determined gravimetrically by filtering 50 mL of runoff water through a preweighed dried filter paper (2V Whatman) and weighing again after drying. Subsamples of runoff water were filtered (0.45 μm pore diameter) before analyses for DRP, nitrate nitrogen (NO_3–N), and ammonium nitrogen (NH_4–N) as described by Self-Davis and Moore (2000). A Lachat flow injection instrument (Loveland, CO) was used for the DRP and inorganic N analyses.

For *E. coli* enumeration, samples were collected in autoclaved 500-mL sample bottles at three different times during each runoff event. Immediately following collection, the samples were placed on ice and analyzed within 24 h of collection. Appropriate volumes of sample were filtered through 0.45-μm Millipore filters (Fisher Scientific, Pittsburgh, PA) and the filters were placed on Difco (Detroit, MI) modified membrane-thermotolerant *E. coli* (modified mTEC) agar and incubated at 44.5°C for 24 h (USEPA Method 1603). Red and magenta colonies were enumerated as *E. coli*. For each plot, the concentrations of *E. coli* in all three samples collected over the 30-min runoff event were averaged.

Background soil samples from 0 to 5 and 5 to 10 cm soil depth were collected before treatment application. Soil samples were extracted with Mehlich-3 extractant (M3) (Mehlich, 1984) using 2 g soil in a 1:10 soil/extractant ratio, shaken for 30 min, and filtered through Whatman filter paper (2V) for the determination of P and metals using ICP (Table 1). Table 2 presents selected site information of plot and runoff parameters.

Statistical Analysis System (SAS Institute, 1999) was used to perform ANOVA using PROC GLM procedure to determine treatment effects and check for interactions. Least significant difference (LSD) method was used to separate means at the 0.05 probability level.

Table 1. Initial soil chemical analyses, Mehlich 3 extraction, except for pH, C, and N and nutrient composition of broiler litter applied in May 2006.

Parameter	pH	N	C	P	K	Ca	Mg	Al	Cu	Fe	Mn	Na	Zn
		g kg^{-1}						mg kg^{-1}					
						Soil							
Depth, cm													
0–5	6.12	2.15	24.00	0.18	0.39	1.26	0.19	672	11	48	42	42	12
5–10	5.77	0.89	10.00	0.06	0.12	0.61	0.07	750	3	45	26	29	2
						Litter							
	6.91	32.96	295.78	26.07	48.25	39.21	10.91	3821	1284	5178	1103	12,474	1097

Table 2. Mean of selected site information and runoff parameters for plots used for rainfall simulation.

Treatment	Soil temperature	Soil water content	Time to runoff
	°C	$m^3\ m^{-3}$	min
		Runoff 1	
Control	17.9	0.201	80.3
Fertilizer	17.9	0.201	61.3
Broadcast litter	17.9	0.201	20.3
Subsurface litter	17.9	0.201	17.3
		Runoff 2	
Control	25.8	0.193	50.3
Fertilizer	25.8	0.193	50.0
Broadcast litter	25.8	0.193	48.7
Subsurface litter	25.8	0.193	23.7
		Runoff 3	
Control	29.7	0.184	73.7
Fertilizer	29.7	0.184	48.0
Broadcast litter	29.7	0.184	56.7
Subsurface litter	29.7	0.184	77.3
		Runoff 4	
Control	26.8	0.182	46.7
Fertilizer	26.8	0.182	50.0
Broadcast litter	26.8	0.182	49.0
Subsurface litter	26.8	0.182	67.0

Table 3. pH and concentrations of selected constituents in runoff 1 to 4, corresponding to 1, 8, 15, and 22 d after litter/fertilizer application to tall fescue plots.

Runoff constituents	Control	Fertilizer	Litter (broadcast)	Litter (subsurface band)
			Runoff 1	
pH	7.5 b†	7.8 a	7.3 c	7.5 b
NH_4–N, mg L^{-1}	0.18 c	10.01 a	7.33 b	0.52 c
NO_3–N, mg L^{-1}	0.32 b	0.34 b	2.40 a	0.31 b
Total suspended solids, g L^{-1}	0.58 a	0.52 a	0.43 b	0.23 c
			Runoff 2	
pH	7.5 a	7.4 a	7.4 a	7.5 a
NH_4–N, mg L^{-1}	0.69 c	12.91 a	4.96 b	1.51 c
NO_3–N, mg L^{-1}	2.47 b	3.68 a	3.48 a	1.83 b
Total suspended solids, g L^{-1}	0.26 b	0.29 b	0.61 a	0.17 b
			Runoff 3	
pH	7.3 b	7.3 b	7.3 b	7.5 a
NH_4–N, mg L^{-1}	0.66 c	8.16 a	2.93 b	0.48 c
NO_3–N, mg L^{-1}	1.65 b	2.23 ab	3.08 a	1.48 b
Total suspended solids, g L^{-1}	0.20 b	0.14 b	0.37 a	0.17 b
			Runoff 4	
pH	7.6 a	7.5 ab	7.4 b	7.4 b
NH_4–N, mg L^{-1}	0.59 b	4.24 a	0.87 b	0.23 c
NO_3–N, mg L^{-1}	0.77 b	1.11 b	1.46 b	2.46 a
Total suspended solids, g L^{-1}	0.31 a	0.02 b	0.43 a	0.13 b

† Within each row (constituent), means followed by the same letter are not significantly different according to LSD 0.05 level.

Results and Discussion

Effect of Litter Application Method

Litter application method had little effect on runoff pH, which ranged from 7.3 to 7.8 for all runoff events; but the application method clearly and substantially affected nutrient concentrations in runoff (Table 3). For example, mean concentrations of NH_4–N were 93% less in runoff from subsurface banded litter than in runoff from broadcast litter during the first simulated rainfall event. That pattern was maintained in all four runoff events, as NH_4–N concentrations were significantly lower in runoff from the banded treatment compared to the surface broadcast application, regardless of runoff timing. Furthermore, NH_4–N concentrations in runoff from the banded treatment remained statistically as low as those in runoff from the control plots that received no nutrient applications at all (Table 3).

Effects on NO_3–N concentrations were similar to those for NH_4–N concentrations in runoff from poultry litter treatments. Subsurface banding the litter application decreased NO_3–N concentrations to control-plot levels (far below NO_3–N concentrations from broadcast litter), except in Runoff 4 (Table 3). The elevated NO_3–N concentrations from banded treatments in runoff 4 may be attributed to the presence of good conditions for nitrification during the 22-d interval between litter application and the runoff event. In particular, the natural rainfall event (16 d after litter application) likely provided plenty of soil moisture during the final week of the study to stimulate activity by soil microbes that convert NH_4–N into NO_3–N. This observed increase in NO_3–N levels is consistent with results reported by Adams et al. (1994) on NO_3–N leaching from poultry manure.

Because NH_4–N was a major N component of the commercial fertilizer used in this study, it is not surprising that NH_4–N concentrations were consistently (all four runoff events) much greater in runoff from the inorganic fertilizer treatments than from any poultry litter treatment. However, NO_3–N was a much smaller N component of the commercial fertilizer; and in every runoff event, NO_3–N concentrations in runoff from the inorganic fertilizer treatments were similar to mean NO_3–N levels from a poultry litter treatment. In runoff 1, NO_3–N concentrations in runoff from the commercial fertilizer were statistically equal to those from the subsurface banded litter. In subsequent

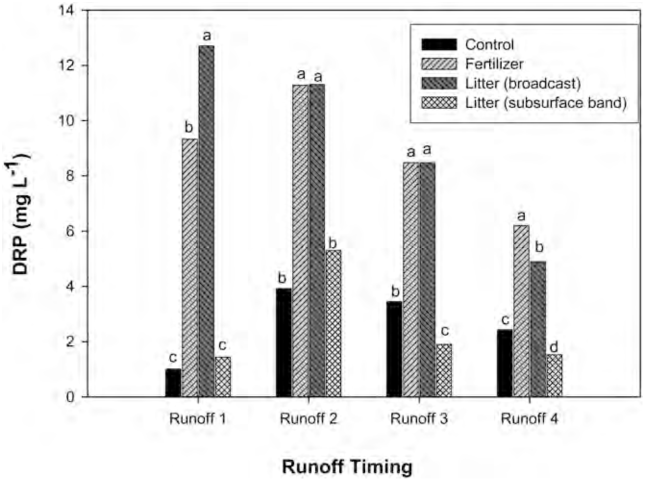

Fig. 2. Concentration of dissolved reactive phosphorus (DRP) in runoff from tall fescue plots treated with broiler litter or fertilizer. Within each runoff event, bars with the same letter indicate no significant difference according to LSD 0.05 level.

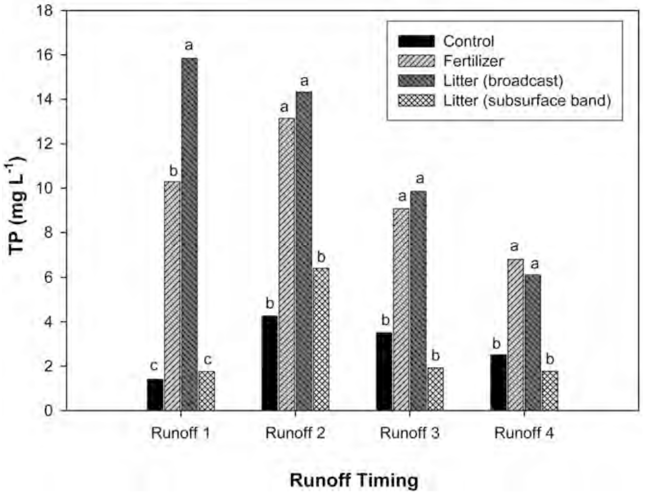

Fig. 3. Concentration of total phosphorus (TP) in runoff from tall fescue plots treated with broiler litter or fertilizer. Within each runoff event, bars with the same letter indicate no significant difference according to LSD 0.05 level.

runoff events, NO_3–N concentrations in runoff from the commercial fertilizer were statistically equal to those from surface broadcast litter (Table 3).

Mean concentrations of TSS observed in runoff from this study were generally small (<0.61 g L^{-1}) because lush forage growth effectively protected the soil against erosion from this pasture site. However, subsurface banding provided the best protection, as this litter application method always yielded smaller TSS concentrations than the surface broadcast method (Table 3).

The effects of poultry litter application method on P concentrations in runoff were very similar to its effects on NH_4–N concentrations, regardless of runoff timing. In runoff 1, mean concentrations of DRP and TP from subsurface litter banding method were about 89% less than from the broadcast method. These results are consistent with the 80 to 95% decreased nutrient losses in runoff observed by Pote et al. (2003) when they incorporated poultry litter into bermudagrass pasture and compared results to surface-applied litter. Throughout all four runoff events in our study, mean concentrations of DRP in runoff from subsurface banded litter were no greater than in runoff from the control plots that received no nutrient applications, while DRP concentrations in runoff from broadcast litter and commercial fertilizer were several times greater (Fig. 2). The total P (TP) concentrations in runoff from all treatments (Fig. 3) followed the same trend as DRP concentrations, reflective of the fact that about 81% of the TP in runoff was in the form of DRP, regardless of litter-application method. Sharpley et al. (1992) also reported that the DRP fraction was the dominant form of P in runoff from pastures and hayfields, and attributed this to the low rates of soil erosion from such sites.

Concentrations of *E. coli* in runoff from the broadcast litter treatment were significantly greater than in runoff from the other treatments for all runoff events (Fig. 4). These results would be expected for the commercial fertilizer and control treatments because they received no poultry litter, but runoff from the subsurface banded litter also had very little *E. coli* contamination. Indeed, our observation that *E. coli* concentrations from the banded treatments were not statistically different from the control or fertilizer treatments suggests that subsurface banding of litter is an effective strategy for reducing pathogen losses from litter-applied fields. Because incorporation of manure into the soil may actually extend pathogen survival compared to surface manure applications, in part because the soil protects the pathogens from UV irradiation and may limit their exposure to desiccation (Hutchison et al., 2004), the reduction in *E. coli* observed in runoff from the banded treatments compared to the surface-applied treatments is due to reducing or eliminating the interaction between the runoff water and the manure.

Nutrient loss (load) was calculated as the mean nutrient concentration in a plot's runoff multiplied by the total runoff volume from that plot; but in this study, total runoff volumes were statistically the same for all treatments in all runoff events (Table 4). This is consistent with results from a study by Sauer et al. (1999), who reported no significant differences in runoff volume among manure-treated tall fescue plots. Because runoff volume was not affected by treatment, the treatment effects on nutrient losses followed approximately the same pattern as their effects on nutrient concentrations in runoff. For example, TP losses from subsurface banded litter application were significantly less (92, 76, 88, and 61% for runoff events 1–4, respectively) than from broadcast litter applications, and were statistically equal to losses from the control treatment (Table 4). Therefore, subsurface banding of poultry litter eliminates contact between litter and the surface runoff water, which results in reduction of the litter nutrient transport through surface runoff water.

In general, nutrient losses from the subsurface litter banding treatment were not significantly different from the control, but were substantially less than nutrient losses from broadcast litter. This indicates that subsurface litter banding could be an effective management practice to reduce nutrient losses in runoff events that occur within 4 wk after litter application.

In general, the TSS losses observed in this pasture study were relatively small (<91 kg ha^{-1}) compared to TSS losses reported from

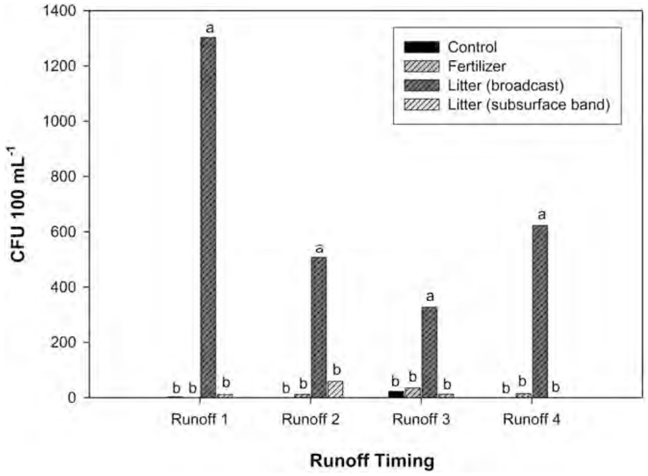

Fig. 4. Concentration of *Escherichia coli* in runoff from tall fescue plots treated with broiler litter or fertilizer. Within each runoff event, bars with the same letter indicate no significant difference according to LSD 0.05 level. If bar is not present, then average concentrations are zero. Detection limit was 4 cfu 100 mL^{-1}.

row crops or bare soil. The TSS losses from subsurface banded litter were never greater than from the controls, but were significantly less than from broadcast litter. We believe the configuration of the single-band litter applicator device and tractor tires caused the litter bands in each subsurface banded plot to be trafficked by the tractor tires after litter had been applied in the band. Therefore the compaction of the soil above these litter bands likely reduced the soil erosion and consequently the TSS from the subsurface band treatment relative to surface broadcast treatment.

Effect of Runoff Timing

Increasing the time between litter application and the first runoff event resulted in reduced nutrient concentrations and total losses from surface broadcast litter, but had little effect on nutrient concentrations and losses in runoff from subsurface banded litter. For broadcast litter, mean NH_4–N concentration decreased from 7.33 mg L^{-1} in Runoff 1 to 0.87 mg L^{-1} in Runoff 4 (Table 3); and mean DRP concentration decreased from 12.7 to 4.90 mg L^{-1} (Fig. 2), but remained well above the critical concentration range (0.002–0.09 mg L^{-1}) required for algal growth (Manahan, 1991; Wood et al., 1999). The TP concentrations in runoff from broadcast litter followed a similar downward trend, falling more than 70% over the four runoff events (Fig. 5). These results are consistent with those of Adeli et al. (2006), who reported that TP concentration was significantly less in runoff generated 9 d after a broadcast litter application compared to TP concentration in runoff generated immediately after applying the litter to bermudagrass. In contrast, the nutrient (NH_4–N, DRP, and TP) concentrations from subsurface banded litter in Runoff 4 were not significantly different from those in Runoff 1, and never exceeded background (control) levels. A significant upward spike in concentration observed during Runoff 2 was likely due to environmental factors rather than treatment effects because it appeared simultaneously in the control and all other treatments except the broadcast litter. Similar temporal increases in nutrient concentration have been observed previously in runoff from unfertilized field sites, and were attributed primarily to P release from senescent plant and microbial tissues as seasonal climate conditions became hotter and drier (Pote et al., 1999). For the broadcast litter treatment, the overwhelming concentrations of nutrients from the litter application may have helped mask the upward spike in nutrient concentrations from background sources that occurred during Runoff 2. In any case, the fact that nutrient concentrations in runoff from banded litter exceeded those from control plots only once (NO_3–N in Runoff 4 as discussed above) provides strong evidence that subsurface banding of litter applications can help minimize most nutrient losses up to 22 d after litter application.

Table 4. Constituent losses (load) from fescue plots treated with fertilizer and two methods (broadcast vs. subsurface banding) of broiler litter in four runoff (runoff 1–4) events corresponding to 1, 8, 15, and 22 d after treatments applications.

Runoff constituents	Control	Fertilizer	Litter (broadcast)	Litter (subsurface band)
			Runoff 1	
Total P, g ha^{-1}	100 b	1977 a	2780 a	223 b
DRP†, g ha^{-1}	71 b	1986 a	2266 a	181 b
NH_4–N, g ha^{-1}	15 c	2139 a	1271 b	63 c
NO_3–N, g ha^{-1}	31 b	75 b	498 a	41 b
Total suspended solids, kg ha^{-1}	50 b	86 a	76 a	30 b
Total runoff volume, L	31 a	41 a	64 a	49 a
			Runoff 2	
Total P, g ha^{-1} ‡	606 c	2751 a	1940 b	470 c
DRP, g ha^{-1}	477 b	1968 a	1554 ab	412 b
NH_4–N, g ha^{-1}	112 c	2773 a	640 b	118 c
NO_3–N, g ha^{-1}	411 b	701 a	458 b	134 c
Total suspended solids, kg ha^{-1}	48 b	53 ab	91 a	19 c
Total runoff volume, L	65 a	69 a	55 a	45 a
			Runoff 3	
Total P, g ha^{-1}	435 b	1324 a	1792 a	223 b
DRP, g ha^{-1}	447 b	1286 a	1445 a	213 b
NH_4–N , g ha^{-1}	88 c	1251 a	540 b	60 c
NO_3–N, g ha^{-1}	202 b	365 a	547 a	155 b
Total suspended solids, kg ha^{-1}	21 b	23 b	62 a	19 b
Total runoff volume, L	52 a	57 a	64 a	44 a
			Runoff 4	
Total P, g ha^{-1}	274 b	711 a	711 a	276 b
DRP, g ha^{-1}	257 b	625 a	579 a	248 b
NH_4–N, g ha^{-1}	65 c	399 a	117 b	55 c
NO_3–N, g ha^{-1}	84 c	118 b	278 a	310 a
Total suspended solids, kg ha^{-1}	30 b	2 c	48 a	21 b
Total runoff volume, L	41 a	41 a	42 a	59 a

† DRP = dissolved reactive phosphorus.

‡ Within each row (constituent), means followed by the same letter are not significantly different according to LSD 0.05 level.

Runoff timing also affected concentrations of *E. coli* in runoff from the broadcast litter plots. For instance, the concentration of *E. coli* dropped from 1.3 × 10^3 cfu 100 mL^{-1} in Runoff 1 to 5.1 × 10^2 cfu 100 mL^{-1} in Runoff 2 for the broadcast litter

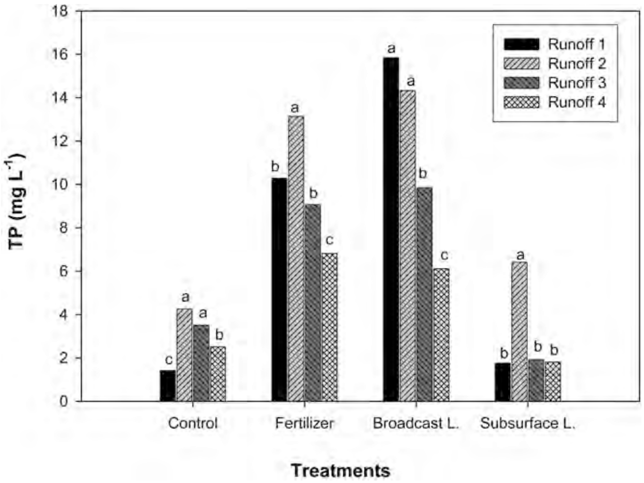

Fig. 5. Total phosphorus (TP) concentrations in runoff from tall fescue plots treated with fertilizer or broiler litter applied by broadcast or subsurface banding methods. Within each treatment, bars with the same letter indicate no significant differences according to LSD 0.05 level.

treatment (Fig. 4), a statistically significant decrease ($P < 0.05$). Concentrations of *E. coli* then remained statistically unchanged during Runoff events 3 and 4 ($P > 0.05$). The results suggest that *E. coli* survival in broiler litter initially declines following surface application but stabilizes afterward, findings consistent with observations of *E. coli* survival in cattle manures (Kudva et al., 1998; Thelin and Gifford, 1983). Therefore, surface-applied broiler litter may continue to be a source of pathogenic microorganisms for prolonged periods of time (Moriya et al., 1999; Kapperud et al., 1998). And while placing manure beneath the soil surface may further extend pathogen survival (Hutchison et al., 2004), incorporating manure into the soil will greatly reduce the contact of runoff water with pathogen-contaminated manure and therefore subsurface banding should be viewed as an effective management strategy for reducing pathogen runoff losses from fields where broiler litter is applied, as we have demonstrated in this study.

Conclusions

In the first runoff event, losses of all nutrients analyzed (NH_4–N, NO_3–N, DRP, and TP) were more than 10 times greater from surface broadcast litter than from subsurface banded litter. In fact, nutrient losses in runoff from subsurface banded litter were not significantly different than from control plots (where no litter had been applied). The *E. coli* losses in runoff from subsurface banded litter were also at background (control) levels, while losses of *E. coli* in runoff from surface broadcast litter were more than 100 times greater than those in runoff from subsurface banded litter and control treatments. Therefore, we concluded that broiler litter application method clearly affected nutrient and *E. coli* losses in runoff, as subsurface banding the litter kept losses at background levels, but surface broadcasting the litter substantially increased losses.

Nutrient and *E. coli* losses from surface broadcast litter were mitigated somewhat by increasing the time between litter application and the first runoff event, but those losses remained significantly greater than losses from controls and subsurface banded litter, regardless of runoff timing. The only exception occurred in the fourth runoff event when NO_3–N losses in runoff from all litter treatments were statistically equal due to favorable soil conditions for mineralization and nitrification of litter N. However, total NO_3–N losses from surface broadcast litter during the entire study were almost triple those from subsurface banded litter. Significant reductions of *E. coli* in runoff from the broadcast litter occurred between runoff 1 and runoff 2, but stabilized afterward. Therefore, surface-applied broiler litter may continue to be a source of pathogenic microorganisms for extended periods of time, while subsurface litter banding moves the pathogen source away from the surface runoff zone and thereby helps protect water supplies by decreasing the risk of pathogen transmission via surface runoff.

Concentrations of TSS found in runoff from this study were generally small (0.02–0.61 g L^{-1}) because lush forage growth effectively protected the soil against erosion from this pasture site. In general, the TSS losses were relatively small (2–91 kg ha^{-1}) compared to the TSS losses reported from row crops. However, total TSS losses in runoff from subsurface banded litter were consistently (all four runoff events) less than half as large as TSS losses from surface broadcast litter.

Our overall conclusion was that subsurface banding of broiler litter into tall fescue pasture greatly reduced nutrient and *E. coli* losses in runoff compared to the traditional surface-broadcast practice. Increasing the time between litter application and the first runoff event was a less effective and less consistent technique for reducing the nutrient and *E. coli* losses from surface broadcast litter. Furthermore, the application timing technique is very limited as a practical management option for producers because long-term weather forecasting can be extremely inaccurate. In contrast, this study indicated that mechanized subsurface litter banding could be a very effective management practice to help prevent poultry litter applications from degrading the quality of surface waters if the method can be fully developed as a practical option for producers.

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