Water-Quality Effects of Incorporating Poultry Litter into Perennial Grassland Soils

D. H. Pote,* W. L. Kingery, G. E. Aiken, F. X. Han, P. A. Moore, Jr., and K. Buddington

ABSTRACT

Poultry litter provides a rich source of nutrients for perennial forages, but the usual practice of surface-applying litter to pastures can degrade water quality by allowing nutrients to be transported from fields in surface runoff, while much of the NH_4–N volatilizes. Incorporating litter into the soil can minimize such problems in tilled systems, but has not been used for perennial forage systems. In this study, we minimized disturbance of the crop, thatch, and soil structure by using a knifing technique to move litter into the root zone. Our objective was to determine effects of poultry litter incorporation on quantity and quality of runoff water. Field plots were constructed on a silt loam soil with well-established bermudagrass [*Cynodon dactylon* (L.) Pers.] and mixed grass forage. Each plot had 8 to 10% slopes, borders to isolate runoff, and a downslope trough with sampling pit. Poultry litter was applied (5.6 Mg ha^{-1}) by one of three methods: surface-applied, incorporated, or surface-applied on soil-aeration cuts. There were six treatment replications and three controls (no litter). Nutrient concentrations and mass losses in runoff from incorporated litter were significantly lower (generally 80–95% less) than in runoff from surface-applied litter. By the second year of treatment, litter-incorporated soils had greater rain infiltration rates, water-holding capacities, and sediment retention than soils receiving surface-applied litter. Litter incorporation also showed a strong tendency to increase forage yield.

Poultry production has become the primary source of income for many small family farms throughout the southeastern United States, especially in mountainous areas where soils have historically been low in fertility. Beef cattle often provide a supplementary income for poultry producers because the litter (manure mixed with bedding material) by-product of poultry production contains significant quantities of plant nutrients and is most commonly used as a surface-applied fertilizer for hay meadows and perennial pastures.

Poultry litter applications have greatly increased the forage and beef outputs from land that had previously been considered marginal for agricultural production. However, the practice of surface-spreading litter has raised serious water quality concerns in some areas. For example, several studies (e.g., Giddens and Barnett, 1980; Westerman et al., 1983; McLeod and Hegg, 1984; Edwards and Daniel, 1993; Shreve et al., 1995) have shown that nutrients and coliforms can be leached from surface-applied litter by heavy rainfall and transported from the field in surface runoff. Also, poultry feed rations are often fortified with dosages of copper (Cu) that are passed through the birds but remain in the litter, so high concentrations of soluble Cu in runoff may be a possible concern. Therefore, producers need the option of improved management methods that decrease runoff losses from poultry litter while making the valuable nutrients more available to crop plants. Incorporation into the soil has proven to be an effective technique for decreasing volatilization and runoff losses from organic fertilizers in some cropping systems. For example, when dairy manure was injected into the soil, Ross et al. (1979) reported that N and P losses in runoff were almost completely eliminated, and Thompson et al. (1987) found that N losses through ammonia volatilization were reduced from 25% to less than 1%. In laboratory experiments, Giddens and Rao (1975) found that incorporating poultry manure into the top 10 cm of soil reduced NH_3–N volatilization by 55% and approximately doubled the NO_3–N concentration in the soil. A field study by Giddens and Barnett (1980) showed that incorporating poultry litter into the soil surface (10 cm) also reduced coliform counts in runoff.

Nichols et al. (1994) reported that incorporation of surface-applied poultry litter did not improve runoff water quality from fescue pasture, but acknowledged that the shallow (2 to 3 cm) rotary-tillage method they used significantly damaged the grass–thatch soil cover and did not adequately turn litter under the soil surface. They suggested that nutrient losses in runoff might be reduced by a less disruptive incorporation method that more effectively moves poultry litter below the soil surface.

In this study, we minimized disturbance of the soil structure, forage crop, and thatch by using a knifing technique to incorporate poultry litter below the surface of established grassland. No previous studies have investigated the effects of using such a technique to move poultry litter from the surface runoff zone into the root zone of established perennial forages, but it could potentially offer multiple benefits. We hypothesized that incorporating poultry litter into the soil would improve water quality by decreasing transport of litter components (nutrients, coliforms, etc.) in runoff.

The amount of organic matter that can be maintained in any soil is largely dependent on the amount of organic N present, and increasing a soil's N level is requisite for increasing its organic C content (Brady, 1990). Therefore, if poultry litter incorporation increases the soil N level, it may also increase organic C levels, while decreasing NH_3 and CO_2 emissions to the atmosphere.

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Abbreviations: EC, electrical conductivity.

Increases in soil N and organic matter are generally associated with improved fertility, cation exchange capacity, structure, tilth, aeration, and/or water-holding capacity of soil (Brady, 1990), and thus could possibly increase forage yields as well. However, our primary objective in this study was to determine the effects of poultry litter incorporation on quantity and quality of runoff water.

MATERIALS AND METHODS

Field plots for this study were constructed in a hillside pasture with 8 to 10% slopes on an Enders silt loam (fine, mixed, active, thermic Typic Hapludults) in Logan County, Arkansas. With occasional applications of commercial fertilizer (e.g., 224 kg of 17–17–17 fertilizer per ha in August 1998), the well-established bermudagrass and mixed grass forage crop had maintained approximately 100% ground cover as measured by the line-transect method (Laflen et al., 1981). Soil sampling and analysis (Mehlich 3) showed that soil P levels initially averaged 50 mg kg^{-1} across the upper part of the hillside, 28 mg kg^{-1} across the mid-level, and less than 18 mg kg^{-1} across the lower part of the hillside. Because the whole hillside was needed to provide adequate space for the experiment, the possibility of initial soil P influencing the results was minimized by constructing a complete block of plots on each level of the hillside. Each plot (2 × 2 m) was fitted with (i) aluminum borders (extending 5 cm above and 10 cm below the surface) to isolate plot runoff and (ii) a downslope trough with sampling pit for runoff collection as described by Edwards and Daniel (1993). A fence constructed around the plots prevented any grazing, damage, or other livestock effects during the course of the study.

Broiler litter (rice hull bedding) was collected from a commercial poultry house, mixed thoroughly, and stored in plastic bags at 4°C until applied to the plots. Litter samples were analyzed for water content, N, P, K, Ca, C, NH_4–N, NO_3–N, Cu, pH, and electrical conductivity (Table 1). Water content was measured gravimetrically, pH and electrical conductivity (EC) meters were used to obtain readings on a mixture of 10 g of manure and 20 mL of water, and mineral concentrations were determined by digesting samples in concentrated HNO_3 and H_2O_2 before analyzing with an inductively coupled plasma spectrophotometer. Total C and total N were determined by weighing a litter sample into a ceramic boat and using dry combustion to release C and N gases for measurement (C by infrared detection, N by thermal conductivity cell). The cadmium reduction colorimetric method was used to measure NO_3–N and a salicylate–sodium nitroprusside colorimetric method was used to measure NH_4–N in the filtrate from 0.5 g of litter extracted with 30 mL of 2 *M* KCl.

Early in the growing season, litter was applied to each plot (except three control plots) at a rate of 5.6 Mg ha^{-1} using one of three application methods: surface-applied, incorporated, or surface-applied on soil-aeration cuts. For surface applications, the poultry litter was scattered uniformly over the plot surface. Soil-aeration cuts were made in twelve of the remaining plots at each 20-cm interval of the plot length by using a steel blade (45 × 9.7 cm) to slice the soil surface (across the slope) to a depth of 8 cm. Each cut extended the width of the plot. On half of these aerated plots, poultry litter was incorporated by placing it directly in the aeration cuts and stepping on the cut to establish better soil contact. The remaining half of the aerated plots were treated by scattering the litter uniformly over the plot surface. Treatments were assigned to plots in a randomized block design and there were six replications of each treatment (two replications within each block), plus three control plots (one in each block).

Table 1. Composition of poultry litter applied to field plots in 1999 and 2000.

Property	Value 1999	Value 2000
H_2O, %†	23.20	18.70
Total N, %	2.38	3.54
Total P, %	0.98	1.08
Total K, %	2.02	2.08
Total Ca, %	1.48	2.01
Total C, %	28.46	30.16
NH_4–N, mg kg^{-1}	1 497	3 306
NO_3–N, mg kg^{-1}	1 716	25.8
Copper, mg kg^{-1}	540	189
pH	7.6	6.9
EC‡, μS cm^{-1}	8 870	10 810

† All percentages are on an "as-is" basis. Other concentrations are on a dry-weight basis.
‡ Electrical conductivity.

One day after the first year (1999) treatment applications, an unexpected 65-mm natural rainstorm produced significant runoff from all plots, and a sample of this natural runoff was collected from each plot. A portion of each water sample was filtered through a 0.45-μm Metricel membrane (Pall Corp., East Hills, NY) to separate suspended solids from dissolved solids, and all water samples were stored in the dark at 4°C until analysis was complete. Four days after the 1999 treatment applications, simulated rainfall was applied (50 mm h^{-1}) to produce 20 min of runoff from each plot using a rainfall simulator based on the design by Miller (1987). For each plot, the time to runoff was recorded and all of the runoff from that plot was pumped into a large container, measured, and mixed thoroughly, and a subsample was taken for analysis. Again, a portion of each sample was filtered and all samples were stored in the dark at 4°C until analyzed.

Treatment applications, simulated rainfall (four days after treatments), and sampling were repeated in the 2000 growing season as described above, but this time no natural rainstorms occurred between the litter applications and the simulated rainfall event. Therefore, the 2000 runoff data represent the most scientifically controlled conditions for a first runoff event following the poultry litter applications.

Filtered samples were analyzed for pH, EC, total dissolved solids, dissolved organic C, NO_3–N, NH_4–N, dissolved PO_4–P, and Cu, while unfiltered samples were analyzed for total suspended solids, total P, total Kjeldahl nitrogen, coliforms, and *Salmonella*.

Soluble salt concentration was estimated by EC and solution pH was determined using a pH meter and combination electrode (Thomas, 1996). Total dissolved solids concentration was determined by weighing the residue obtained from evaporating a known quantity of filtered runoff solution (Rhoades, 1996). Dissolved organic C was measured with an organic carbon analyzer (TOC-5000; Shimadzu, Kyoto, Japan). Concentrations of NO_3–N and PO_4–P in filtered runoff solution were determined by ion chromatography (Model DX 500; Dionex, Sunnyvale, CA). A series of standard solutions were analyzed after each 15 samples to check instrumental shift. Concentrations of NH_4–N in solution were measured by ammonium electrode (Thermo Orion, Beverly, MA) (Mulvaney, 1996). Copper in filtered solution was determined by inductively coupled plasma emission spectrometry for the first year (1999) and by atomic absorption spectrophotometry for the second year (2000) samples.

Total suspended solids were determined gravimetrically by weighing a dry filter membrane, shaking a known quantity of

unfiltered runoff, filtering through the membrane, then drying and reweighing the filter membrane with the runoff residue enclosed. Following a sulfuric acid digest of unfiltered runoff samples, total P was determined by the ascorbic acid colorimetric method (Murphy and Riley, 1962) and total Kjeldahl N concentrations were determined by the automated phenate method (Method 351.2; USEPA, 1983). Solids were separated (centrifuged) from the unfiltered water samples, plated on *Salmonella–Shigella* agar plates, and incubated. The plates are specifically selective for these two bacteria, so the absence of bacterial colonies on sample slides indicated that *Salmonella* and *Shigella* were not present in the runoff water. Coliform bacteria were measured by using known amounts of unfiltered runoff sample to inoculate a series of tubes of lactose broth. After incubation, the most probable number (MPN) of coliforms per 100 mL of runoff was estimated by the number of tubes that tested positive for gas production. The presence of coliforms was confirmed by using positive-testing tubes to inoculate Levine's eosin methylene blue (EMB) agar plates and Endo agar plates, incubating, and examining the plates for nucleated bacterial colonies on EMB agar and for red colonies on Endo agar. These colonies were then used to inoculate a nutrient agar slant and complete their identification as gram-negative, non-spore-forming, rod-shaped bacteria (coliforms) by examining them on a gram-stained slide under oil.

Throughout the first (1999) growing season, measurements of forage yield were taken at 21-d intervals by harvesting from the center area (47 × 107 cm) of each plot down to a forage height of 2.5 cm. To maintain a better stand of forage during the second (2000) growing season, the cutting height was adjusted to 5.0 cm, and forage yield was measured at 28-d intervals.

Experimental results were analyzed by using the general linear models (GLM) procedure to identify significant differences ($\alpha = 0.05$) between the means (SAS Institute, 1996). Each mean represented six samples (from the six replications of the treatment), except the control mean, which represented three samples. Results were compared to determine the effect of incorporation on each measured runoff parameter.

RESULTS AND DISCUSSION

Forage Yield

The study of total forage yield was limited by drought conditions that prevailed late in the growing seasons of both 1999 and 2000. Forage on treated plots responded well to the litter and mean yields on treated plots were at least 250% of mean yield on control plots, regardless of the year or application method. In both years, mean yield was approximately 25% higher on plots where litter was incorporated than on plots where it was surface-applied, but yields were variable so the differences were not always significant at the $\alpha = 0.05$ level. In any case, the litter incorporation process apparently had no detrimental effects on forage yield, and actually showed a strong tendency to increase yield, possibly in response to increased retention of litter nutrients in the forage root zone.

Rain Infiltration and Runoff Rates

Because the first runoff samples collected in 1999 were taken from the sampling pits following an intense, uncontrolled natural rainfall event, no accurate measurement could be made of the amount of rain required to initiate runoff, total runoff volume, or infiltration rate. However, the simulated rainfall events provided the necessary data to study hydrological impacts for second (1999) and first (2000) runoff events following poultry litter application. Due to drier conditions that prevailed between litter application and the simulated rainfall event in 2000, the average amount of rain required to generate 20 min of runoff from each field plot in 2000 was approximately double the amount required in 1999 (Table 2). When treatment effects were compared, the amount of rain required tended to be larger for plots that received poultry litter than for control plots, regardless of the litter application method or the year in which it was applied. This is not surprising, given that poultry litter could be expected to absorb and hold some of the water applied to the plot surface, but treatment differences were still not always significant ($\alpha = 0.05$) due to the variability within treatments. Only the aerated plots required significantly more rain than controls in 1999, but plots where litter had been incorporated clearly required the most rain ($\alpha = 0.05$) to produce runoff in 2000. The reason(s) for this effect have not yet been confirmed, but the fact that plots where litter was incorporated tended to produce more forage supports the possibility that these plots may have also required more moisture to support increased evapotranspiration. Another possibility is that litter incorporation in 1999 may have attracted soil metazoans (earthworms, etc.) and/or stimulated better root growth and soil structure that eventually resulted in more extensive macropore development, faster infiltration, and greater water-holding capacity. This remains speculative, however, because metazoan populations, root growth, and macropore development were not measured.

In both 1999 and 2000, runoff volumes tended to be larger (5–27%) from surface-applied litter than from aerated or incorporated litter application methods; however, runoff volumes were also highly variable within treatments, so there were no significant ($\alpha = 0.05$) treatment effects on runoff volume in either year (Table 2). However, because the amount of rain required to produce runoff was greater in 2000 for the litter-incorpo-

Table 2. Mean rainfall, runoff, and infiltration rate of simulated rain applied at 50 mm h^{-1} to perennial grass plots treated with poultry litter by various methods.

Litter treatment	Rain†	Runoff	Infiltration rate
	mm	mm	mm h^{-1}
		1999, Runoff 2	
Control, no litter	21.9a‡	14.3a	16.8a
Surface-applied	24.7ab	13.2a	23.0a
Surface-applied to aerated soil	28.0b	12.1a	28.0a
Incorporated	24.0ab	12.5a	21.9a
		2000, Runoff 1	
Control, no litter	39.4A	4.3A	44.2AB
Surface-applied	48.8A	6.0A	43.7A
Surface-applied to aerated soil	49.2A	5.2A	44.2AB
Incorporated	66.6B	4.7A	46.4B

† Amount required to produce 20 minutes of runoff.
‡ Each mean represents six runoff events, except the controls (three runoff events). Within each column, means followed by the same letter are not significantly different ($\alpha = 0.05$).

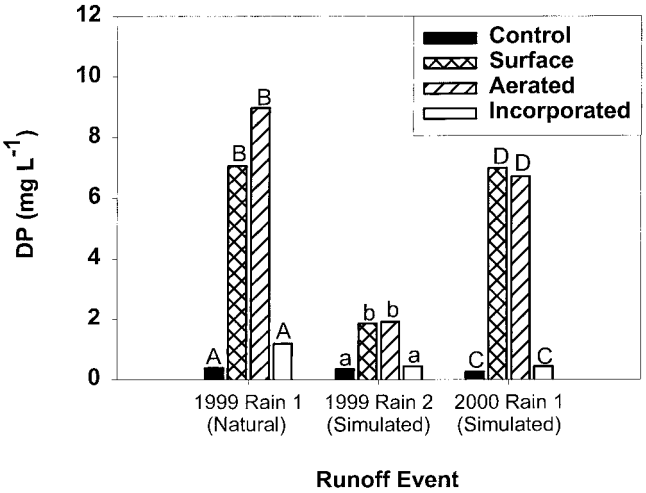

Fig. 1. Effect of poultry litter application method on dissolved phosphate phosphorus (DP) in pasture runoff. Within each runoff event, bars with the same letter indicate treatment results that are not significantly different (α = 0.05).

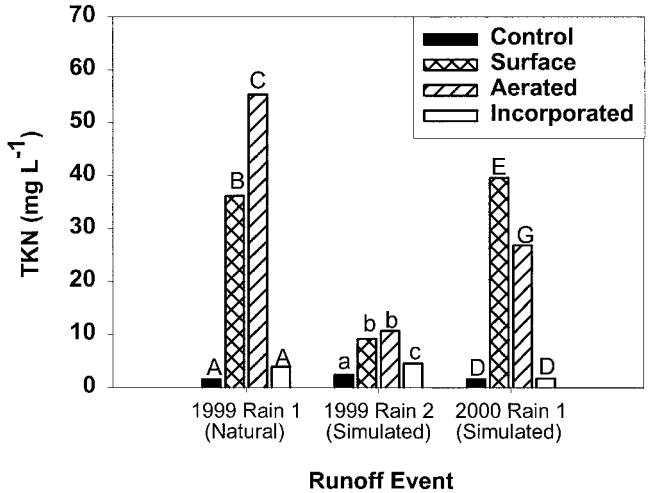

Fig. 2. Effect of poultry litter application method on total Kjeldahl nitrogen (TKN) in pasture runoff. Within each runoff event, bars with the same letter indicate treatment results that are not significantly different (α = 0.05).

rated plots, they had significantly higher mean infiltration rates than surface-applied plots that year.

Water Quality

Most measures of runoff water quality were strongly affected by poultry litter application method. For example, mean dissolved PO_4–P concentrations were much lower (α = 0.05) in runoff from incorporated litter than from surface-applied litter during all three runoff events, and aeration of plots where litter was surface-applied had no significant effect on those results (Fig. 1). Most of the P in plot runoff was in the dissolved form, so it is not surprising that these same treatment effects were also apparent for total P concentrations in runoff (Table 3). Furthermore, mean concentrations of dissolved PO_4–P and total P in runoff from incorporated litter were statistically no higher (α = 0.05) than from control plots where no litter was applied.

Incorporating litter into the soil also decreased nitrogen losses in runoff. Total Kjeldahl N concentrations in runoff from incorporated litter were far below those observed in runoff from surface-applied litter (α = 0.05) and similar to levels in runoff from control plots where no litter was applied (Fig. 2). The NH_4–N fraction is an important N component of fresh litter that can easily volatilize as NH_3 or be transported in runoff. Mean concentration of NH_4–N in the first runoff from surface-applied litter varied from 25 mg L^{-1} (uncontrolled natural rainstorm, 1999) to 12 mg L^{-1} (simulated rainstorm, 2000). This apparent decline may have been due to the extra three days that were available in 2000 for NH_3 volatilization before the first rainfall event, but any di-

Table 3. Mean constituent concentrations in runoff after poultry litter application (5.6 Mg ha^{-1}) to perennial grass plots.

Runoff constituent	Control (no litter)	Surface-applied	Surface-applied to aerated soil	Incorporated
	Litter application method†			
		1999, Runoff 1 (natural rain)		
NO_3–N, mg L^{-1}	0.49a	0.40a	0.39a	0.57a
Total P, mg L^{-1}	0.75a	10.25b	12.48b	1.46a
Total dissolved solids, mg L^{-1}	83a	464b	575b	172a
Total suspended solids, mg L^{-1}	19a	58a	94a	18a
pH	6.79a	7.38b	7.35b	7.02a
EC‡, µS cm^{-1}	42.1a	551.5b	564.1b	152.7a
		1999, Runoff 2 (simulated rain)		
NO_3–N, mg L^{-1}	0.30a	4.25b	4.53b	0.67a
Total P, mg L^{-1}	0.56a	2.96b	3.27b	0.77a
Total dissolved solids, mg L^{-1}	174a	271b	278b	196a
Total suspended solids, mg L^{-1}	71a	107b	104b	89ab
pH	7.25a	7.58b	7.61b	7.34a
EC, µS cm^{-1}	136.0a	243.2b	278.3b	191.5c
		2000, Runoff 1 (simulated rain)		
NO_3–N, mg L^{-1}	3.36a	5.69a	4.77a	7.91a
Total P, mg L^{-1}	0.61a	8.85b	8.25b	0.85a
Total dissolved solids, mg L^{-1}	163a	380b	303ab	245ab
Total suspended solids, mg L^{-1}	137a	438b	353b	147a
pH	7.01a	7.26a	7.34a	7.19a
EC, µS cm^{-1}	153.6a	577.9b	465.1b	157.8a

† Within each row (constituent), means followed by the same letter are not significantly different according to Fisher's LSD (α = 0.05).
‡ Electrical conductivity.

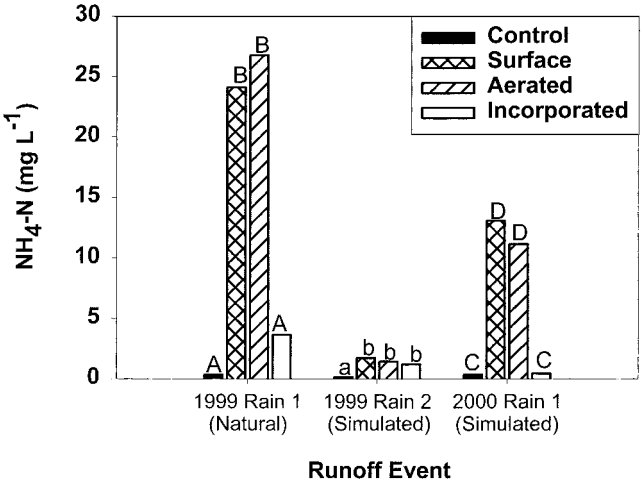

Fig. 3. Effect of poultry litter application method on NH_4–N in pasture runoff. Within each runoff event, bars with the same letter indicate treatment results that are not significantly different (α = 0.05).

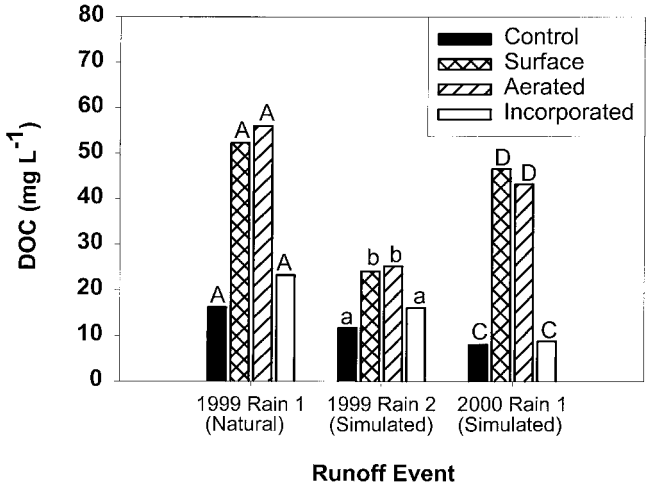

Fig. 4. Effect of poultry litter application method on dissolved organic carbon (DOC) in pasture runoff. Within each runoff event, bars with the same letter indicate treatment results that are not significantly different (α = 0.05).

rect comparisons between 1999 data and 2000 data are difficult because other factors may also vary between an uncontrolled natural rain event and a controlled simulated rain event. Mean NH_4–N concentrations in the first runoff from incorporated litter were less than 4 mg L^{-1} in 1999 and only 0.4 mg L^{-1} in 2000 (Fig. 3), levels that were not significantly higher (α = 0.05) than from control plots in each of those events. Therefore, incorporation effectively prevented most NH_4–N loss in the first runoff from a litter application. However, in the second runoff event (1999), very little NH_4–N was detected in runoff from any of the litter treatments. Much of the NH_4–N was leached from the litter during the previous rainstorm and some was probably volatilized to the atmosphere, but conditions (pH, aeration, moisture, temperature) at the soil surface in the early growing season also become favorable for the nitrification process whereby aerobic soil microbes convert NH_4–N into NO_3–N. Evidence for this transformation is shown by the mean NO_3–N concentrations in runoff from surface-applied litter being more than 10 times higher in the second runoff than in the first runoff (Table 3), while NH_4–N concentrations had dropped to less than 2 mg L^{-1} in the second runoff (Fig. 3).

Mean concentrations of dissolved organic C in runoff from incorporated litter were close to levels in runoff from control plots (Fig. 4). This effect was very similar to incorporation effects on N and P concentrations, and was evident in all three runoff events. Surface-applied litter produced the highest dissolved organic C concentrations, regardless of aeration status, and the difference was significant for both simulated rainstorms, but results in the uncontrolled natural rainstorm (1999) were too variable for differences to be significant at the α = 0.05 level.

Copper was not detectable in runoff from incorporated litter or control plots during any of the three rainfall events, so litter incorporation apparently eliminated almost all runoff losses of this soluble heavy metal (Fig. 5). Mean copper concentrations in runoff from surface-applied litter ranged as high as 0.542 mg L^{-1}, and were not significantly affected by aeration of the soil surface.

Runoff from these perennial grass plots tended to be low in sediments. In fact, it usually contained higher concentrations of dissolved solids than suspended solids (Table 3). Mean concentrations of dissolved solids and suspended solids were never significantly higher (α = 0.05) in runoff from incorporated litter than from control plots, but were consistently higher in runoff from surface-applied litter. The differences were generally significant for the simulated rainstorms, but suspended solid concentrations in runoff from the uncontrolled natural rainstorm were too variable for differences to be significant at the α = 0.05 level. Again, aeration of the soil surface had no significant effect (Table 3).

Treatment effects on mean pH and EC readings (Table 3) followed the same pattern as constituent concentrations: the highest levels occurred in runoff from surface-applied litter with no significant effect from soil aeration, while levels in runoff from incorporated litter

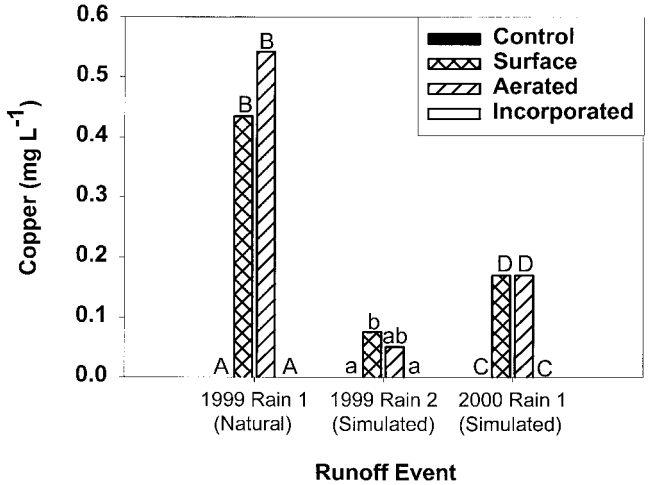

Fig. 5. Effect of poultry litter application method on copper in pasture runoff. Within each runoff event, bars with the same letter indicate treatment results that are not significantly different (α = 0.05).

were lower and usually statistically equivalent ($\alpha = 0.05$) to control plot readings. The EC readings indicate a higher concentration of ions (dissolved salts) in runoff from surface-applied litter than from incorporated litter. Poultry litter is known to raise soil pH levels because of its high Ca content (Table 1), so it is not surprising that pH was highest in runoff with increased concentrations of soluble litter constituents. These pH differences were significant in both 1999 runoff events, but not significant in the 2000 runoff at the $\alpha = 0.05$ level (Table 3).

No *Salmonella* were detected in any plot runoff during this study. The most probable number of coliforms averaged 121, 377, 587, and 486 for the control, incorporated, aerated, and surface-applied treatments, respectively, in runoff from the simulated rainfall (1999), and overall concentrations were similar in runoff from the uncontrolled natural rainstorm. During the natural and simulated rainstorms, mean coliform counts tended to be lower in runoff from incorporated litter than from surface-applied litter, but results were too variable for the differences to be significant ($\alpha = 0.05$). Because no significant differences were detected in either natural or simulated rainstorms during 1999, the extra sampling work, analytical work, and supplies required to measure these bacterial parameters were discontinued for the 2000 runoff event.

In general, runoff from the second rainstorm following poultry litter application tended to be cleaner (have lower nutrient concentrations) than runoff from the first rainstorm (Fig. 1–5), because a high percentage of soluble components is leached by the first runoff and no longer available for the second runoff. The NO_3–N component is a notable exception (Table 3), because it tends to increase with time if conditions are favorable for nitrification.

Soil aeration used in conjunction with surface-applied litter has drawn considerable interest because it was hoped that this treatment would provide a method of retaining litter nutrients that could be easily adopted by producers and implemented with existing farm equipment. By slicing the soil across the path of water flows, it was thought that this technique might funnel nutrient constituents into the soil and prevent their transport from the field in runoff. There were some indications that such an effect may have occurred to a limited extent in these runoff events. For example, the fact that the mean rainfall required to generate 20 min of runoff tended to be larger for aerated plots than for other surface-applied plots (Table 2) suggests a delay in the onset of runoff. The 2000 runoff data (third data set in Table 3 and Fig. 1–5), which represent the most scientifically controlled conditions for a first runoff event following poultry litter applications, also show a strong trend toward aerated plots having better runoff quality than other surface-applied plots. Total Kjeldahl N was significantly lower ($\alpha = 0.05$), and other parameters such as EC tended to be lower ($p < 0.16$), in runoff from aerated plots. However, such effects were not always consistent in other runoff events.

From a hydrological viewpoint, it seems likely that aeration cuts may indeed help hold runoff and nutrients in the early stages of a runoff event, but once the soil is saturated and soil cuts are filled with water, a layer of runoff water will tend to flow through litter on the soil surface in a direction parallel to the surface and directly across the top of any cuts in the soil. Because incorporated litter is placed only in the soil cuts, runoff flowing as a layer of surface water would tend to pass above the litter and leave the nutrients relatively undisturbed except for a gradual downward movement of water within the soil cuts. Therefore, incorporation of litter into soil cuts can apparently provide effective control of most nutrient losses throughout the runoff event,

Table 4. Mean constituent losses (loads) in runoff from simulated rainfall after poultry litter application (5.6 Mg ha^{-1}) to perennial grass plots.

Runoff constituent	Litter application method†			
	Control (no litter)	Surface-applied	Surface-applied to aerated soil	Incorporated
	g ha^{-1}			
		1999, Runoff 2		
Dissolved organic C	1 705a	3 200b	3 065bc	2 168ac
NO_3–N	41a	554b	560b	78a
NH_4–N	21a	232b	175ab	165ab
Total Kjeldahl N	357a	1 213b	1 290b	615a
Dissolved phosphate P	47a	246b	232b	52a
Total P	78a	390b	396b	99a
Cu	0a	10b	6ab	0a
Total dissolved solids	25 404a	35 528a	33 754a	26 151a
Total suspended solids	10 117a	14 034a	12 590a	11 720a
		2000, Runoff 1		
Dissolved organic C	370a	2 989b	2 463b	434a
NO_3–N	142a	321a	263a	415a
NH_4–N	16a	857b	641b	21a
Total Kjeldahl N	73a	2 536b	1 422c	87a
Dissolved phosphate P	11a	455b	381b	23a
Total P	26a	557b	468b	41a
Cu	0a	11b	10b	0a
Total dissolved solids	7 704a	24 335a	16 067a	11 959a
Total suspended solids	6 009a	28 958b	19 341ab	6 867a

† Within each row (constituent), means followed by the same letter are not significantly different according to Fisher's LSD ($\alpha = 0.05$).

while aeration cuts seem to lose their effectiveness as a runoff event progresses.

Mass loss (load) of a litter constituent in runoff is the product of two factors: the volume of runoff from the plot and mean concentration of the constituent in that runoff. Because each of these factors has considerable variability in field situations, an inherent result is that variability tends to be magnified in their product. Consequently, significant differences between mass losses in runoff can be more difficult to detect than significant differences between runoff volumes or constituent concentrations. However, in this case, both factors tended to decrease when litter was incorporated rather than surface-applied. Although decreases in runoff volume were not considered significant (Table 2), decreases in concentration of most litter constituents were significant (Table 3 and Fig. 1–5). Therefore, mass losses of most litter constituents were also significantly less ($\alpha = 0.05$) when litter was incorporated rather than surface-applied. This result was evident when simulated rainfall in 1999 generated the second runoff after litter application, but was even more apparent when simulated rainfall produced the first runoff after litter application in 2000 (Table 4).

CONCLUSIONS

The results of this study provide strong evidence that using a knifing technique to incorporate poultry litter into perennial grassland soils can improve water quality when compared with surface-applying the litter. Data from all three rainfall events showed that litter incorporation significantly decreased nutrient concentrations and mass losses in runoff from litter applications, and the decreases were usually more than 80%. By the second growing season, litter-incorporated soils also exhibited greater rain-infiltration rates, water-holding capacities, and sediment retention than soils receiving surface-applied litter. Furthermore, litter incorporation showed a strong tendency to increase forage yield.

This study was only designed to objectively evaluate potential benefits of incorporating poultry litter into perennial grassland. Although much more research will be required for the knifing technique to be mechanized and fully evaluated as a practical management option for producers, this study clearly demonstrated that incorporating litter into grassland can help retain water and nutrients in the soil.

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