SEDIMENT AND NUTRIENT LOSSES FROM FIELD-SCALE CROPLAND PLOTS TREATED WITH ANIMAL MANURE AND INORGANIC FERTILIZER

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(Received 22 August 2005; accepted 12 February 2006)

Abstract. A field-scale plot study was conducted at Virginia Tech's Prices Fork Research Farm, to evaluate the transport of nutrients in runoff from manure and fertilizer applied at P-based agronomic rates to cropland planted to corn. Simulated rainfall events representing 2- to 10-year storms in southwest Virginia, occurring 1 and 2 days following manure and fertilizer application were used to generate runoff. Plots were treated with surface applied poultry litter, surface applied and incorporated dairy manure, incorporated inorganic fertilizer, and no fertilizer (control). Application rates were based upon agronomic phosphorus (P) requirements of corn. The concentration of total suspended solids and nutrients decreased from the first to the second simulated rainfall event; however, the edge-of-field mass loss or yield increased due to increased runoff volume. Surface application of dairy manure resulted in 25–50% lower runoff volumes and 35–60% lower total suspended solid yields when compared to surface applied poultry litter. Surface applied poultry litter produced the greatest total P and dissolved reactive P losses. Results of this study suggest that manure applied based on crop P requirements can still yield significant edge-of-field nutrient losses, if rainfall occurs soon after application.

Keywords: dairy manure, nitrogen, nutrients, phosphorus, poultry litter, rainfall simulator

1. Introduction

Excessive or ill-timed land application of animal manure can impair water quality by introducing pollut-ants such as nutrients, organic matter, sediment, patho-gens, heavy metals, hormones, and antibiotics (Harkin, 1997). Agricultural nonpoint source (NPS) pollution is a major water quality concern throughout the United States and the world. The 2000 National Water Quality Inventory reported that runoff from agricultural lands was the leading source of water quality impairments (USEPA, 2002). Sediment from cropland is a major cause of water pollution and excessive sediments in water can reduce the amount of sunlight reaching aquatic plants; excessive sediments in water bodies can also cover fish spawning areas, clog the gills of fish and hence disrupt the aquatic food chain (Myers *et al.*, 1985). The physical, chemical and biological damages associated with sediment costs about $16 billion annually in North America (ARS, 2003). Sediments can also transport adsorbed pollutants such as heavy metals and nutrients.

Water, Air, and Soil Pollution (2006) 175: 61–76
DOI: 10.1007/s11270-006-9111-4

Nitrogen (N) and Phosphorus (P) are two important plant nutrients; however, excess amounts of these nutrients in aquatic ecosystems can cause eutrophic conditions. In the United States, about 20% of assessed rivers/streams (approx. 84,600 km), 50% of assessed lakes, reservoirs and ponds (about 1.55 million ha), and approximately 12% of estuaries (about 5,000 sq km) are impaired due to excessive nutrients (USEPA, 2002). According to the 2002 303 (d) list of impaired waters in Virginia, about 74 km of rivers/streams, 600 ha of lakes and about 400,000 ha of estuaries are impaired due to excessive nutrients (VADEQ, 2004).

Several plot- and field-scale studies have been conducted to assess the impact of manure or inorganic fertilizer on agricultural lands, their application rate, and application method on the total suspend solids (TSS) transported in surface runoff (Bruggeman and Mostaghimi, 1993; Tobbara, 2003; Vories *et al.*, 2001). Plot- and field-scale studies have also been conducted to determine the losses of nutrients from agricultural land (Edwards and Daniel, 1993, 1994; Eghball and Gilley, 1999; Heathman *et al.*, 1995). A plot-scale study by Wood *et al.* (1999) compared nutrient losses from inorganic fertilizer and poultry litter surface applied to cropland. They reported the presence of sufficient inorganic N in the runoff from both treatments to support algal growth in lakes. Eghball and Gilley (1999) conducted rainfall simulations to compare the effect on runoff water quality from tilled and no-till cropland treated with beef cattle manure, reporting higher P concentration from N-based manure applications when compared with P-based manure applications with no significant difference in crop yield.

A better understanding of sediment and nutrient losses from land-applied animal manures is needed to improve the design of best management practices (BMPs) and NPS modeling associated with the development and implementation of Total Maximum Daily Loads (TMDLs) and other similar watershed management processes. Although many field studies have been conducted to investigate the composition of runoff from pasture lands, only a few have reported on the composition of runoff from cropland.

The objective of this study was to determine sediment and nutrient losses from conventionally tilled plots receiving different types of animal manure and inorganic fertilizer applied on P-based agronomic rates. The sediment and nutrient losses were induced by simulating rainfall events equivalent to 2- to 10-year storms in southwest Virginia occurring one- and two-days following manure and fertilizer application.

2. Materials and Methods

Sediment and nutrient transport plots were constructed at the Virginia Tech Prices Fork Research Center, Blacksburg, VA. The soil at the site is Groseclose silt loam (clayey, mixed, mesic Typic Hapludult). Five treatments were evaluated; dairy manure surface applied (DS), dairy manure incorporated (DI), poultry litter surface applied (PL), inorganic fertilizer incorporated (IF), and no fertilizer or control (CO).

Three replications of each treatment produced 15 plot Randomized Complete Block Design (RCBD). Plots were planted with "Early Sunglow Sweet" corn (Zea Mays) at a rate of 10.8 kg ha^{-1} following manure application on May 13, 2003.

2.1. Plot construction

An area approximately, 25 m × 50 m, was tilled twice, each time to a depth of 0.15 m. Following the second tillage operation, 2, 4-Dichlorophenoxyacetic acid (at the rate of 0.57 kg active ingredient per ha) was applied to kill any emergent weeds. Following the tillage operations, fifteen 18.3 m × 3.3 m plots were constructed, each adjacent to another with the plot longitudinal direction perpendicular to the contours. The average slope of the study area is 2%. The plots were separated by 0.30 m wide plywood borders, buried to a depth of 0.15 m. The borders served to isolate each plot hydrologically. At the downslope end of each plot a "V" shaped outlet concentrated the overland flow into a 0.15 m rectangular H-flume fitted with a Belfort model FW-1 stage recorder (Belfort Instrument, Baltimore, MD, USA) which continuously measure runoff rate. Runoff rate and volume from the plots were also recorded manually using a stop watch and a 5-liter bucket.

2.2. Manure characteristics and application rates

Soil samples were collected following the second tillage operation and analyzed for residual nutrient content to determine the appropriate fertilizer rate. Recommended N and P (as P_2O_5) application rates were 170 kg ha^{-1} and 90 kg ha^{-1}, respectively (VADCR, 1995, p. 34). Dairy manure was obtained 17 days prior to the experiment from an anaerobic lagoon located at the Virginia Tech dairy, Blacksburg, VA and stored in plastic tanks. The dairy manure was collected early to accommodate the dairy's lagoon pump-out schedule. During the lagoon pump-out, lagoon contents were well mixed. Dairy manure samples were sent to Agriculture Service Laboratory, Clemson University, Clemson, SC, on the day of manure collection and application (Table I). The amount of dairy manure applied to the DI and DS treatments was based on this analysis. Poultry litter was obtained from a broiler operation one day before it was applied. The poultry litter nutrient analysis data from the previous year (same farm, same management system) was used to determine litter application rates for the PL treatment (Table II).

Poultry litter and dairy manure samples were collected on the on the day the material was applied to determine the actual amount of nutrients applied to each treatment. According to day of application test results, the amount of P applied to the PL treatment was about 27% more than the target agronomic rate of 90 kg ha^{-1} and about 16% less than the target for the DI and DS treatments (Table III).

Dairy manure was applied on each plot manually by transferring the stored manure to buckets that were used to uniformly spread the manure. To resuspend

TABLE I

Concentration and availability of nutrients in manure and fertilizer used in the experiment as reported by the Agriculture Service Laboratory, Clemson University, Clemson, SC

Manure	Available nitrogen	Phosphorus as P_2O_5
Dairy Manure (4/26/03)[a]	9.74×10^{-4}(kg L^{-1}) − Surface Applied[b] / 1.2×10^{-3}(kg L^{-1}) − Incorporated[c]	7.97×10^{-4} (kg L^{-1})
Dairy Manure (5/13/03)	9.9×10^{-4}(kg L^{-1}) − Surface Applied / 1.18×10^{-3}(kg L^{-1}) − Incorporated	6.7×10^{-4} (kg L^{-1})
Poultry Litter (Previous year record, same farm and management system)[d]	2.25%[e]	2.46%
Poultry Litter (5/13/03)	2.00%	3.12%
Ammonium Nitrate	34.00%	–
Triple Super Phosphate	–	45.00%

[a]Dates in parenthesis refer to the day when manure was shipped for nutrient analysis, and the results are used for calculating dairy manure application rate.
[b]Surface applied available nitrogen includes 50% of ammonium-N, 60% of organic-N, and 100% of nitrate-N, in dairy manure.
[c]Incorporated available nitrogen includes 80% of ammonium-N, 60% of organic-N, and 100% of nitrate-N, in dairy manure.
[d]Data used to calculate the rate of poultry litter application.
[e]All percentages are reported by weight.

TABLE II

Amount of manure and fertilizer applied to each treatment

Treatment	Manure/fertilizer applied for P_2O_5	N deficiency fulfilled by urea (kg ha^{-1})	Urea applied (kg ha^{-1})
DS (Surface Applied Dairy Manure)	112,923 (L ha^{-1})	60.0	176.0
DI (Incorporated Dairy Manure)	112,923 (L ha^{-1})	34.5	101.5
PL (Surface Applied Poultry Litter)	3,660 (kg ha^{-1})	88.0	258.0
IF (Incorporated Inorganic Fertilizer)	200 (kg ha^{-1}) (TSP)[a]	170.0	500.0
CO (Control)	–	–	–

[a]Triple Super Phosphate.

TABLE III

Amount of nutrients applied to each treatment (kg ha^{-1})

Treatment	Total N applied to each treatment using animal manure and inorganic fertilizer	Amount of phosphorus (P) applied to each treatment
DS (Surface Applied Dairy Manure)	172.0	75.0
DI (Incorporated Dairy Manure)	168.0	75.0
PL (Surface Applied Poultry Litter)	161.2	114.0
IF (Incorporated Inorganic Fertilizer)	170.0	90.0
CO (Control)	0.0	0.0

the solids, the dairy manure was constantly stirred while being transferred to the buckets. Poultry litter was uniformly broadcast by hand. Any crop N requirement not met by the P-based agronomic manure application was supplied in the form of uniformly broadcast Urea-N (Table II). Triple Super Phosphate (TSP) was applied to the inorganic fertilizer plots. For the incorporated treatments, dairy manure and inorganic fertilizer were incorporated by tilling the soil to a depth of 0.15 m after application. Corn was planted shortly after manure application at the rate of 10.8 kg ha^{-1}.

2.3. Rainfall simulation

The Virginia Tech Biological Systems Engineering rainfall simulator (Dillaha *et al.*, 1988) was set up following corn planting to conduct a series of rainfall simulations. The source water used for simulation was obtained from an on-site pond. A source-water sample was collected from the inlet line for each simulated event and analyzed for TSS and nutrients. Rainfall was applied at a rate of 50 mm h^{-1}. The coefficient of uniformity for the two events was greater than 90%. The first rainfall simulation (S1) was conducted on May 14, 2003, within 24 hrs of manure application, to simulate a scenario where a rainfall event occurs shortly after manure application. The S1 event lasted 60 minutes and represented a precipitation event occurring on dry soil conditions. The second rainfall simulation (S2) was conducted 24 hrs later (May 15, 2003), and represented nutrient transport under wet soil conditions. The duration for S2 event was 48 minutes. The duration of simulated rainfall events was a function of the time required for the runoff from the plots to reach steady-state conditions.

2.4. Sampling and data analysis

Runoff grab samples from each plot were collected at the outfall of the flumes every three minutes on the rising limb of the hydrograph. This interval was increased to six minutes after the runoff hydrograph reached steady-state. Simulated rainfall events continued until the hydrograph from all plots reached steady state. Between 8 and 14 water samples were collected from each plot during each rainfall/runoff event. One flow-weighted composite sample for each plot and each simulated event was prepared, following the event, and stored in a cooler. The flow weighted samples were analyzed for total suspended solids and nutrients including ammonium-nitrogen, nitrate-nitrogen, total kjeldahl nitrogen, dissolved reactive phosphorus, bioavailable phosphorus, and total phosphorus (Clesceri *et al.*, 1998).

2.5. Statistical analysis

Analysis of variance (ANOVA) was conducted for runoff volumes, TSS, nutrient concentration, and yield to determine treatment and simulation effects (Ott and

Longnecker, 2001). An adjusted Tukey's pairwise comparison (Ott and Longnecker, 2001) was performed among the treatments and rainfall simulation events. Significance was determined at the $P < 0.05$ level. The null hypotheses were that there is no difference in (a) runoff characteristics, (b) sediment concentrations and yield, and (c) nutrient concentrations and yield, among treatments within each simulated event and among the simulated events.

3. Results and Discussion

3.1. Runoff

The effect of antecedent soil moisture conditions was evident on the peak runoff rate and runoff volume for the two simulated events (Table IV). The event mean peak runoff rate and volume were significantly greater for the S2 event, some 25% and 53% greater, respectively when compared to S1. Before the S1 event, the soil was dry and freshly tilled, the plot surface was disturbed, and the infiltration capacity was greater for the two rainfall simulation events. The S1 event settled the tilled soil smoothing the surface. Additionally, raindrop impact redistributed soil particles producing a surface sealing crust. The surface crust and the additional soil moisture

TABLE IV

Mean of runoff responses from the treatments for all simulated events

Treatments	Simulated event (S1)		Simulated event (S2)	
	Mean treatment peak runoff rate (mm/hr)			
DI (Incorporated Dairy Manure)	32.1a[a]	(10.9)[b]	39.6a	(7.77)
PL (Surface Applied Poultry Litter)	28.6a	(4.8)	37.2a	(1.92)
DS (Surface Applied Dairy Manure)	22.7a	(4.3)	38.4a	(4.73)
IF (Incorporated Inorganic Fertilizer)	38.5a	(4.7)	39.7a	(1.19)
CO (Control)	28.6a	(6.2)	33.0a	(4.76)
Event Mean	30.1A[c]		37.6B	
	Mean treatment runoff volume (mm)			
DI (Incorporated Dairy Manure)	6.5ab	(2.1)	11.9ab	(1.69)
PL (Surface Applied Poultry Litter)	7.9ab	(4.1)	12.0ab	(0.58)
DS (Surface Applied Dairy Manure)	4.1a	(2.2)	8.9a	(1.73)
IF (Incorporated Inorganic Fertilizer)	12.0b	(1.5)	14.2b	(0.73)
CO (Control)	6.3ab	(1.9)	9.5ab	(2.26)
Event Mean	7.4A		11.3B	

[a]Similar lowercase letters indicate no statistically significant difference among the treatments for a simulated event at the 0.05 level.

[b]Numbers in parenthesis are standard deviations.

[c]Similar uppercase letters indicate no significant difference between simulated rainfall events at the 0.05 level.

from the S1 rainfall reduced infiltration capacity for the S2 event. The difference in runoff peaks and volumes largely drives the observed constituent-specific nutrient yield differences.

With respect to treatment effects, the DS treatment produced the smallest peak runoff rate for S1 and smallest runoff volume for both S1 and S2. The mulching effect of the solids in the surface applied dairy manure was likely a contributing factor. A similar mulching effect was observed by Bruggeman and Mostaghimi (1993) for freshly applied sludge. The largest peak runoff rate and volume was observed from IF treatment for both rainfall simulation events.

3.2. Total suspended solids

The TSS results were affected by tillage, surface sealing and smoothing caused by raindrop impact. The event mean TSS concentration was significantly less for S2 compared to S1. However, because of the greater runoff volumes, the S2 event-mean mass loss (yield) was greater (Table V).

The PL treatment produced the greatest TSS concentrations for S1, significantly greater than the DS treatment. Poultry litter was dry, loose and easily transportable

TABLE V

Mean concentration and yield of total suspended solids (TSS) in runoff from different treatments for all the simulation events

	Mean treatment concentration (g L^{-1})			
Treatments	Simulated event (S1)		Simulated event (S2)	
DI (Incorporated Dairy Manure)	3.82ab[a]	(0.55)[b]	3.32a	(0.20)
PL (Surface Applied Poultry Litter)	4.13a	(0.61)	2.84a	(0.54)
DS (Surface Applied Dairy Manure)	2.99b	(0.74)	2.84a	(0.54)
IF (Incorporated Inorganic Fertilizer)	3.64ab	(0.71)	3.11a	(0.23)
CO (Control)	3.41ab	(0.36)	2.66a	(0.53)
Event Mean	3.60A[c]		2.66B	
	Mean treatment yield (kg ha^{-1})			
DI (Incorporated Dairy Manure)	247.8a	(83.4)	396.7ab	(70.6)
PL (Surface Applied Poultry Litter)	340.9a	(205.0)	341.9ab	(77.5)
DS (Surface Applied Dairy Manure)	131.7a	(105.6)	253.7a	(65.0)
IF (Incorporated Inorganic Fertilizer)	440.3a	(119.0)	443.4b	(49.5)
CO (Control)	216.8a	(84.4)	244.5a	(6.9)
Event Mean	275.5A		336.0A	

[a]Similar lowercase letters indicate no statistically significant difference among the treatments for a simulated event at the 0.05 level.
[b]Numbers in parenthesis are standard deviations.
[c]Similar uppercase letters indicate no significant difference between simulated rainfall events at the 0.05 level.

in runoff. The mulching effect of the solids and the settling effect of the surface-applied liquid dairy manure reduced TSS losses compared to plots where the manure/fertilizer was incorporated.

TSS yield was greatest for the IF treatment for both rainfall simulation events (Table V). The inorganic fertilizer was incorporated with a tiller, which loosened the soil, making it more susceptible to removal via runoff. This effect, coupled with the highest runoff volume, resulted in the IF treatment producing the greatest TSS yield. The IF treatment recorded significantly greater TSS yield than DS and CO for the S2 event. Although dairy manure was also incorporated for DI treatment, the liquid dairy manure appeared to produce less soil disturbance during incorporation than was observed for the IF treatment. The DI treatment also produced the second lowest runoff volume, which contributed to the lower TSS yield.

3.3. Phosphorus

Analysis of runoff samples included total phosphorus (TP), dissolved reactive phosphorus (DRP), and bioavailable phosphorus (BAP). DRP includes the amount of reactive P which is in soluble form, and BAP includes all reactive P in soluble and sediment bound phase. The reactive P is readily available for algal uptake in waterbodies. TP includes all forms of P in soluble and sediment bound phases. Although all the TP is not readily available for plant growth, it can be released into ambient water slowly and become bioavailable.

The event mean concentration for TP decreased significantly from S1 to S2 (Table VI). The event mean TP yield also decreased from S1 to S2, but the decrease was not significant since the event-mean runoff volume increased from S1 to S2. The observed TP concentrations showed no significant treatment effect for either simulation event. The PL treatment resulted in greatest TP concentration for both events. High TP concentrations from the CO plots was unexpected, and may have been due to cross contamination from foot traffic across the plots during corn planting, and rainfall simulator set up.

The PL treatment produced the greatest TP yield for both S1 and S2. The PL treatment yield was significantly greater than the DS treatment yield for S1. The results, however, are confounded by the fact that the actual amount of P applied in to the PL treatment was about 1.5 times higher than the P applied in dairy manure treatments. The over application resulted due to 27% greater available P in poultry litter than the nutrient analysis results of previous year which were used to calculate the poultry litter application rate. The dairy manure had 11% lower available P than the nutrient analysis result of older (17days) samples which were used to calculate the dairy manure application rate. In spite of this difference, the TP loss from the PL treatment was approximately 3 times greater than the DS treatment for the S1 event and about 2 times greater for S2. These results suggest that the surface application of poultry litter can lead to higher P loss in runoff than dairy manure.

TABLE VI
Mean concentration and yield of total phosphorus (TP) in runoff

Treatments	Mean treatment concentration (mg L^{-1})			
	Simulated event (S1)		Simulated event (S2)	
DI (Incorporated Dairy Manure)	8.10a[a]	(2.72)[b]	2.00a	(0.85)
PL (Surface Applied Poultry Litter)	10.50a	(2.83)	5.33a	(2.47)
DS (Surface Applied Dairy Manure)	5.90a	(2.70)	3.73a	(1.81)
IF (Incorporated Inorganic Fertilizer)	3.38a	(0.82)	3.03a	(2.40)
CO (Control)	4.93a	(4.23)	1.73a	(0.56)
Event Mean	6.56A[c]		3.17B	
Source Water[d]	0.43		0.31	
	Mean treatment yield(gha^{-1})			
DI (Incorporated Dairy Manure)	496.6ab	(91.9)	245.9a	(134.3)
PL (Surface Applied Poultry Litter)	757.3a	(227.1)	648.1a	(322.2)
DS (Surface Applied Dairy Manure)	274.0b	(258.3)	312.8a	(105.5)
IF (Incorporated Inorganic Fertilizer)	405.3ab	(109.2)	442.0a	(356.2)
CO (Control)	257.9b	(135.2)	160.6a	(49.4)
Event Mean	438.2A		361.9A	

[a]Similar lowercase letters indicate no statistically significant difference among the treatments for a simulated event at the 0.05 level.
[b]Numbers in parenthesis are standard deviations.
[c]Similar uppercase letters indicate no significant difference between simulated rainfall events at the 0.05 level.
[d]Given the relative magnitude of the source water concentration and the runoff results, the source water concentration was not subtracted from runoff data.

The DRP event-mean concentrations decreased significantly from S1 to S2 (Table VII). However, the DRP event-mean yield increased from S1 to S2, again, because there was more runoff volume for the S2 event. The DRP concentrations from the PL treatment were significantly greater than other treatments for both simulated events, by about 2 to 11 times. These results suggest greater availability of dissolved P in poultry litter than dairy manure. A result similar to this was reported by Sharpley and Moyer (2000). The DRP mean-treatment yield from the PL treatment was also significantly greater than all other treatments for the S1, and for the DS treatment for S2. The over application of P in PL treatment makes it difficult to make a definitive statement about the availability of DRP in poultry litter compared to dairy manure. However, it is worth noting that DRP yield from PL treatment was about 10 times greater than the DS and DI treatments in S1, and more than 2 times greater than the DS treatment and 5 times greater for the DI treatment in S2.

Similar to TP and DRP, the BAP event-mean concentration decreased significantly from S1 to S2. This decrease was primarily attributed to the removal of organic particles and sediments in runoff during the S1 event. The BAP event-mean

TABLE VII

Mean concentration and yield of dissolved reactive phosphorus (DRP) in runoff

Treatments	Mean treatment concentration (mg L^{-1})			
	Simulated Event (S1)		Simulated event (S2)	
DI (Incorporated Dairy Manure)	0.37b[a]	(0.18)[b]	0.45c	(0.19)
PL (Surface Applied Poultry Litter)	3.63a	(0.51)	2.07a	(0.20)
DS (Surface Applied Dairy Manure)	0.96b	(0.55)	1.21b	(0.34)
IF (Incorporated Inorganic Fertilizer)	0.84b	(0.52)	0.45c	(0.08)
CO (Control)	0.37b	(0.15)	0.25c	(0.22)
Event Mean	1.23A[c]		0.89B	
Source Water	0.15		0.12	
	Mean treatment yield (g ha^{-1})			
DI (Incorporated Dairy Manure)	26.4b	(21.8)	55.6b	(31.1)
PL (Surface Applied Poultry Litter)	300.3a	(190.2)	248.6a	(35.5)
DS (Surface Applied Dairy Manure)	32.0b	(9.9)	111.3ab	(51.5)
IF (Incorporated Inorganic Fertilizer)	98.3ab	(52.0)	64.3b	(13.7)
CO (Control)	22.4b	(10.7)	26.0b	(28.6)
Event Mean	95.9A		101.2A	

[a]Similar lowercase letters indicate no statistically significant difference among the treatments for a simulated event at the 0.05 level.

[b]Numbers in parenthesis are standard deviations.

[c]Similar uppercase letters indicate no significant difference between simulated rainfall events at the 0.05 level.

yield decreased from S1 to S2, however, the decrease was not statistically significant. The BAP concentration from the PL treatment was significantly greater than all other treatments for both S1 and S2. The BAP yield from PL treatment was greater than all other treatment for both S1 and S2. This difference was statistically significant in S2. Again, these results are confounded by the higher P application for the poultry treatment, however, again the concentration and yield from the PL were approximately 2 or more times greater than the other treatments. The high concentrations from the PL treatment suggest that BAP losses are more likely from surface applied poultry litter.

The comparison of DRP and BAP results reveals that except for PL, the BAP concentrations for all the treatments are 2 to 5 times higher than the DRP concentrations for S1 event. These results suggest that the reactive P in liquid dairy manure may bound to sediment more quickly than the reactive P in dry poultry litter. The lower concentration of DRP for DI treatment, compared to DS suggests that some of reactive P present in dairy manure adsorbed to the soil shortly after its incorporation. A marginal increase in DRP concentrations in runoff from S1 to S2 for the DI and DS treatments, in spite of increased runoff volume, suggests that the release of soluble P from dairy manure is slower than poultry litter and inorganic fertilizer.

TABLE VIII

Mean concentration and yield of bioavailable phosphorus (BAP) in runoff

Treatments	Mean treatment concentration (mg L^{-1})			
	Simulated event (S1)		Simulated event (S2)	
DI (Incorporated Dairy Manure)	2.74a	(1.28)[a,b]	0.85a	(0.18)
PL (Surface Applied Poultry Litter)	4.80b	(0.48)	3.02b	(0.97)
DS (Surface Applied Dairy Manure)	2.24a	(0.15)	1.39a	(0.41)
IF (Incorporated Inorganic Fertilizer)	2.20a	(0.44)	0.91a	(0.47)
CO (Control)	1.92a	(0.47)	0.65a	(0.12)
Event Mean	2.78A[c]		1.37B	
Source Water	0.22		0.17	
	Mean treatment yield (g ha^{-1})			
DI (Incorporated Dairy Manure)	193.0[ab]	(146.0)	102.2[a]	(33.0)
PL (Surface Applied Poultry Litter)	366.3[a]	(153.6)	365.8[b]	(131.7)
DS (Surface Applied Dairy Manure)	92.5[b]	(56.7)	121.1[a]	(24.2)
IF (Incorporated Inorganic Fertilizer)	265.7[ab]	(77.0)	132.1[a]	(72.1)
CO (Control)	122.1[ab]	(49.3)	62.0[a]	(19.2)
Event Mean	207.9A		156.6A	

[a]Similar lowercase letters indicate no statistically significant difference among the treatments for a simulated event at the 0.05 level.
[b]Numbers in parenthesis are standard deviations.
[c]Similar uppercase letters indicate no significant difference between simulated rainfall events at the 0.05 level.

A laboratory study by Sharpley (1997) also reported decreasing DRP concentrations in runoff from soils treated with poultry litter from the first to the tenth rainfall runoff event. The DRP concentrations reported by Sharpley (1997) in their first simulated event were 10–20 times lower than those reported here. TP concentrations were 4–5 times lower than those reported here, although the application rate of P was 10,000 kg ha^{-1}, about three times the rate applied in the present study. The primary reason for this difference may be that the first simulated event in Sharpley's (1997) study occurred 7 days after litter application which allowed enough time for interaction between soil and P, in contrast to the present study, where the first simulated event was conducted within 24 hows of poultry litter application. The results reported here are effectively a worst case scenario where rainfall immediately follows manure application.

These results suggest that surface application of poultry litter can lead to greater reactive P loss in runoff compared to dairy manure. However the concentrations and yields reported in the present study are edge of the field values, where no buffering, filtering or dilution takes place. The magnitude of concentrations reported in present study, however, may cause nutrient overenrichment of surface waters in small agricultural watersheds.

3.4. Nitrogen

Analysis included total kjeldahl nitrogen (TKN), nitrate-nitrogen (NO_3^--N), and ammonium-nitrogen (NH_4^+-N). The observed TKN concentrations in runoff from all the treatments (Table IX) for both rainfall simulation events was an order of magnitude greater than the USEPA criteria of 0.34 mg L^{-1}, for overenrichment of surface water (USEPA, 2000). The observed TKN concentrations were an order of magnitude greater than the NO_3^--N and NH_4^+-N concentrations for both simulation events (Tables X and XI). We speculate that some organic N present in the soil might have contributed to this result. However, the soil was not analyzed for organic N prior to the experiment.

The TKN event-mean concentrations from S1 and S2 were similar. The TKN event-mean yield for S2 was significantly greater than S1, again due to increased runoff volume. PL treatment recorded greatest TKN concentrations for S1, significantly greater than DS. The TKN yield from the PL treatment was more than three times the TKN yield from the DS treatment during S1, suggesting that surface applied dry poultry litter is a greater source of N in runoff than surface applied liquid dairy manure. The S1 TKN treatment yields do not

TABLE IX

Mean concentration and yield of total kjeldahl nitrogen (TKN) in runoff

	Mean treatment concentration (mg L^{-1})			
Treatments	Simulated Event (S1)		Simulated Event (S2)	
DI (Incorporated Dairy Manure)	19.27ab[a]	(2.68)[b]	19.17a	(1.80)
PL (Surface Applied Poultry Litter)	21.08a	(3.83)	18.30a	(4.45)
DS (Surface Applied Dairy Manure)	13.47b	(2.95)	19.03a	(4.55)
IF (Incorporated Inorganic Fertilizer)	15.64ab	(2.02)	14.90a	(1.37)
CO (Control)	12.67b	(1.36)	12.23a	(1.65)
Event Mean	16.43A[c]		16.73A	
Source Water	Not available		1.30	
	Mean treatment yield (g ha^{-1})			
DI (Incorporated Dairy Manure)	1260.8a	(471.0)	2272.2a	(238.0)
PL (Surface Applied Poultry Litter)	1766.4a	(1157.7)	2204.0ab	(603.7)
DS (Surface Applied Dairy Manure)	507.3a	(170.0)	1711.1ab	(527.3)
IF (Incorporated Inorganic Fertilizer)	1867.3a	(257.3)	2124.7ab	(281.6)
CO (Control)	775.8a	(162.8)	1139.9b	(162.6)
Event Mean	1235.5A		1890.4B	

[a]Similar lowercase letters indicate no statistically significant difference among the treatments for a simulated event at the 0.05 level.

[b]Numbers in parenthesis are standard deviations.

[c]Similar uppercase letters indicate no significant difference between simulated rainfall events at the 0.05 level.

TABLE X
Mean concentration and yield of nitrate nitrogen (NO_3^--N) in runoff

Treatments	Mean treatment concentration (mg L^{-1})			
	Simulated event (S1)		Simulated event (S2)	
DI (Incorporated Dairy Manure)	1.33ab[a]	(0.25)[b]	1.40b	(0.10)
PL (Surface Applied Poultry Litter)	1.57ab	(0.16)	1.23b	(0.21)
DS (Surface Applied Dairy Manure)	1.70a	(0.53)	1.97a	(0.06)
IF (Incorporated Inorganic Fertilizer)	1.17ab	(0.12)	1.50b	(0.10)
CO (Control)	1.07b	(0.06)	1.23b	(0.06)
Event Mean	1.37A[c]		1.47A	
Source Water	Not available		0.90	
	Mean treatment yield (g ha^{-1})			
DI (Incorporated Dairy Manure)	86.3aa	(28.9)[b]	167.8ab	(35.1)
PL (Surface Applied Poultry Litter)	121.1a	(52.5)	148.5ab	(31.6)
DS (Surface Applied Dairy Manure)	76.5a	(65.5)	176.3ab	(38.2)
IF (Incorporated Inorganic Fertilizer)	140.1a	(19.8)	213.0a	(7.8)
CO (Control)	67.4a	(23.0)	116.8b	(26.7)
Event Mean	98.3A[c]		164.5B	

[a]Similar lowercase letters indicate no statistically significant difference among the treatments for a simulated event at the 0.05 level.
[b]Numbers in parenthesis are standard deviations.
[c]Similar uppercase letters indicate no significant difference between simulated rainfall events at the 0.05 level.

show any statistical significance due to high standard deviation for PL treatment. The DI treatment did produce significantly greater yields than CO for S2 event.

The NO_3^--N event-mean concentrations were similar between the simulated rainfall events, however due to increased runoff volume a significant increase in NO_3^--N event-mean yield was observed from S1 to S2, (Table X). The DS treatment produced the greatest NO_3^--N concentration, significantly greater than CO for the S1 event. The DS treatment NO_3^--N concentration was significantly greater than the other treatments for the S2 event. No significant treatment effects were observed for NO_3^--N yield for the S1 event, however, the IF treatment did produce significantly greater NO_3^--N yield compared to CO treatment for S2. These results suggest that the manure or fertilizer application can lead to the movement of NO_3^--N in surface runoff if rainfall occurs soon application.

While the PL treatment did produce greater NH_4^+-N concentration and yields when compared to the other treatments, neither the observed concentrations nor yields showed any significant treatment effects for either simulated rainfall event. The event-mean concentrations and yields were not different either. A field study by Vories *et al.* (2001), compared inorganic fertilizer and poultry litter, and reported

TABLE XI
Mean concentration and yield of nitrate nitrogen (NH_4^+-N) in runoff

Treatments	Mean treatment concentration (mg L^{-1})			
	Simulated event (S1)		Simulated event (S2)	
DI (Incorporated Dairy Manure)	1.23a[a]	(1.12)[b]	0.73a	(0.61)
PL (Surface Applied Poultry Litter)	1.42a	(0.14)	1.60a	(1.18)
DS (Surface Applied Dairy Manure)	1.17a	(0.40)	0.97a	(0.72)
IF (Incorporated Inorganic Fertilizer)	0.68a	(0.46)	0.41a	(0.26)
CO (Control)	0.57a	(0.40)	0.09a	(0.10)
Event Mean	1.01A[c]		0.76A	
Source Water	0.07		0.04	
	Mean treatment yield (g ha^{-1})			
DI (Incorporated Dairy Manure)	75.2a	(56.4)	82.0a	(63.6)
PL (Surface Applied Poultry Litter)	115.3a	(64.9)	187.0a	(129.3)
DS (Surface Applied Dairy Manure)	50.4a	(38.0)	79.2a	(45.0)
IF (Incorporated Inorganic Fertilizer)	86.3a	(64.6)	58.7a	(39.1)
CO (Control)	34.4a	(27.6)	8.0a	(9.2)
Event Mean	72.3A		83.0A	

[a]Similar lowercase letters indicate no statistically significant difference among the treatments for a simulated event at the 0.05 level.
[b]Numbers in parenthesis are standard deviations.
[c]Similar uppercase letters indicate no significant difference between simulated rainfall events at the 0.05 level.

slightly higher concentrations of NH_4^+-N in runoff from plots treated with poultry litter similar to what we observed. Edwards and Daniel (1994) conducted a field study on fescue grass and reported higher NH_4^+-N concentrations from plots treated with inorganic fertilizer compared to poultry litter during rainfall simulations conducted 7 and 14 days following manure application.

4. Conclusions

A field-scale plot study was conducted at Virginia Tech's Prices Fork Research Farm, to evaluate the transport of nutrients in runoff from manure and fertilizer applied at P-based agronomic rates to cropland planted to corn. Simulated rainfall events representing 2- to 10-year storms in southwest Virginia, occurring 1 and 2 days following manure and fertilizer application were used to generate runoff. In general, the edge-of-field total phosphorus (TP) and total kjeldahl nitrogen (TKN) concentrations reported in this study were well above the nutrient criteria of 8 μg L^{-1} for P, and 0.34 mg L^{-1} for N recommended by USEPA to prevent overenrichment of waterbodies (USEPA, 2000). However, substantial buffering, filtering, and dilution are expected in large watersheds, which may reduce actual nutrient loadings to a receiving waterbody.

Surface applied dairy manure produced 25 to 50% lower runoff volume, and 35 to 60% lower TSS yield than surface applied poultry litter for the two simulated events. A mulching effect produced by the solids in the liquid dairy manure was thought to be responsible. Surface applied poultry litter produced P losses 2 to 10 times greater than surface applied dairy manure, suggesting that poultry litter even when applied at P-based agronomic rates may be a significant source of P if rainfall occurs soon after application.

The total kjeldahl nitrogen runoff concentrations from all the treatments were at least an order of magnitude greater than $NO_3{}^-$-N and $NH_4{}^+$-N runoff concentrations. This result could be attributed to the presence of excess organic-N in the soil. Surface application of dairy manure resulted in greatest $NO_3{}^-$-N concentrations in runoff for both simulated rainfall events. No significant rainfall simulation event or treatment effects were observed for $NH_4{}^+$-N concentration or yield.

Results of this study suggest that manure applied at P-based agronomic rate can still yield significant edge-of-field nutrient losses, if rainfall occurs soon after application. Results further suggest that of the evaluated treatments, (dairy manure surface applied (DS), dairy manure incorporated (DI), poultry litter surface applied (PL), inorganic fertilizer incorporated (IF), and no fertilizer or contol (CO)) the PL treatment produced the greatest edge-of-field nutrient losses.

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