Published online July 6, 2006

Nutrient Transport from Livestock Manure Applied to Pastureland Using Phosphorus-Based Management Strategies

M. L. Soupir,* S. Mostaghimi, and E. R. Yagow

ABSTRACT

Land applications of manure from confined animal systems and direct deposit by grazing animals are both major sources of nutrients in streams. The objectives of this study were to determine the effects of P-based manure applications on total suspended solids (TSS) and nutrient losses from dairy manures and poultry litter surface applied to pasturelands and to compare the nutrient losses transported to the edge of the field during overland flow events. Two sets of plots were established: one set for the study of in-field release and another set for the study of edge-of-the-field nutrient transport. Release plots were constructed at three pastureland sites (previous poultry litter applications, previous liquid dairy manure application, and no prior manure application) and received four manure treatments (turkey [*Meleagris gallopavo*] litter, liquid dairy manure, standard cowpies, and none). Pasture plots with a history of previous manure applications released higher concentrations of TSS and higher percentages of total P (TP) in the particulate form. Transport plots were developed on pasture with no prior manure application. The average flow-weighted TP concentrations were highest in runoff samples from the plots treated with cowpies (1.57 mg L^{-1}). Reducing excess P in dairy cow diets and surface applying manure to the land using P-based management practices did not increase N concentrations in runoff. This study found that nutrients are most transportable from cowpies; thus a buffer zone between pastureland and streams or other appropriate management practices are necessary to reduce nutrient losses to waterbodies.

Land application of manure from confined animal production facilities is an effective method for disposing of animal waste while supplying nutrients to crops and pastureland. For many years, land application of manure from animal production facilities has been based on the N requirement of the crops. When the N demands of crops are met, excess P available in the source manure is not used, and, as a result, P accumulates in the soils. Phosphorus applied to agricultural lands in the form of animal manures has the potential to be transported to surface waters, leading to eutrophication (Sharpley et al., 1993). Characteristics of eutrophic waters include low oxygen levels, reduced aquatic species diversity, turbidity, and poor taste and odor in water bodies (Hansen et al., 2002). The oxidation of excessive organic matter can depress dissolved oxygen levels below the respiration requirements of fish (Edwards and Daniel, 1994), resulting in fish kills. Concern over the effects of runoff from lands receiving manure applications has led to the development of state-specific agricultural P management strategies (Tarkalson and Mikkelsen, 2004), including P-based management practices when soils exceed state-defined upper limits of soil test P (Sims, 2000).

One method of reducing the P surplus on dairy farms is to lower excess dairy rations of P to meet animal requirements. Several studies have found that reduced dietary P levels result in satisfactory milk yields and decreased P excretion in feces (Wu et al., 2000; Knowlton and Herbein, 2002). Zhengxia et al. (2002) found that the amount and proportion of water-soluble P in fecal samples increased when dietary P rations were increased through the addition of P minerals. Lowering dietary P from 4.8 to 3.8 g P kg^{-1} reduced the crop acreage required for land application by 39% (Powell et al., 2001). When P levels in manure are reduced through such dietary measures, care must be taken to prevent excess land application of N when guided by P-based management practices.

In the past, scientists assumed that P in the soil was generally stable as long as soil erosion was minimized since many soils exhibit a high capacity to sorb P. However, studies have reported that P losses are influenced by soil P levels (Pote et al., 1996; Sharpley, 1995). Pasture or no-till cropland may have DP losses that surpass those from fields with high erosion, thus control of particulate P is not sufficient to prevent eutrophication (Sharpley et al., 1994). The DP has been found to have a greater impact on eutrophication than particulate P (Fozzard et al., 1999). Phosphorus losses from soils are also influenced by P source, method of P application, and timing of rainfall events (Tabbara, 2003; Edwards and Daniel, 1993). Up to 10% of applied P may be present in runoff when an event occurs shortly after surface application of fertilizer or manure (Hansen et al., 2002) with decreasing losses during subsequent rainfall events (Edwards and Daniel, 1994; Kleinman and Sharpley, 2003). Higher manure application rates increase the dissolved reactive P (DRP) in runoff during rainfall events occurring soon after manure application (Kleinman and Sharpley, 2003). Kleinman et al. (2002) found the DRP concentrations in runoff to be strongly correlated with the water-soluble P concentration of manure.

Previous studies have also reported that N losses are influenced by the time period between manure applications and rainfall events (Ross et al., 1978; Edwards and Daniel, 1994; McLeod and Hegg, 1984) and method of application (Heathman et al., 1995; Eghball and Gilley, 1999). Less than 4% of TKN was present in runoff from fescue (*Festuca* spp.) pasture plots receiving dairy ma-

Department of Biological Systems Engineering, Virginia Tech, 201 Seitz Hall, Mail Code 0303, Blacksburg, VA 24061. Received 17 Aug. 2005. *Corresponding author (mpeterie@vt.edu).

Published in J. Environ. Qual. 35:1269–1278 (2006).
Technical Reports: Surface Water Quality
doi:10.2134/jeq2005.0314

Abbreviations: DP, dissolved phosphorus; PP, particulate phosphorus; S1, simulation 1; S2, simulation 2; TKN, total Kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorus.

nure, poultry manure, municipal sludge, and commercial fertilizer at a rate of 112 kg N ha^{-1} (McLeod and Hegg, 1984). Buffer strips located between land application areas and streams may significantly reduce N loading into surface waters (Heathman et al., 1995).

Much of the recent research associated with P runoff has been conducted on pasturelands, but there is a lack of information concerning the potential for increased N levels in runoff when excess P in dairy cow diets is reduced and P-based management practices are required. The objectives of this study were to (i) determine the effects of P-based dairy manures and poultry litter applications on nutrient losses from pastures with different land-use histories and (ii) compare the effects of P-based dairy manures and poultry litter applications on the nutrient losses transported to the edge of the field during overland flow events from pasturelands.

MATERIALS AND METHODS

Plot Construction

Field plots were constructed on existing pastureland in and around Blacksburg, VA. Two sets of plots were established: one set for the study of in-field release and another set for the study of edge of the field nutrient transport.

Release plots were established to compare detachment of nutrients from manures and soils with differing residual soil P levels during rainfall events. Release plots were used to compare nutrient concentrations available in the field during rainfall events and do not represent nutrient concentrations that are transported to the edge of the field. The study evaluated four manure treatments (turkey litter, liquid dairy manure, standard cowpies, and none or control) and three pasturelands with different histories: previous poultry litter applications (Turkey Farm), previous liquid dairy manure applications (Dairy Farm), and no prior manure applications (Tech Research Farm). The Turkey Farm site was rotationally grazed by beef cattle, the Dairy Farm was continuously grazed by dairy cattle and the Tech Research Farm was exclusively used for hay production. Prefabricated steel borders were placed in the soil to construct 1 by 1 m release plots. Runoff drained through a small flume and was collected down-slope. The runoff volume was determined by weighing the collected runoff. The slopes of the release plots averaged 8.2% Each treatment was replicated twice at the Tech Research Farm and three times at the Turkey Farm and Dairy Farms. Thus, a total of 32 plots were constructed.

Transport plots were constructed at the Tech Research Farm to measure the concentration and yield of nutrients present in overland flow at the edge of the field. The transport of nutrients from plots treated with turkey litter, liquid dairy manure, and standard cowpies were compared to control plots on which no animal waste was applied. Two replications of each treatment resulted in the construction of a total of eight transport plots. Each transport plot was 3 m wide by 18.3 m long on an approximate 5.5% slope. Plywood borders were placed to a depth of 15 cm along the plot boundaries. A “V”-shaped outlet was placed at the down-slope end of each plot to direct runoff into a 0.15 m (6-in) H-flume equipped with an FW-1 stage recorder for continuous flow measurement.

Soils and Nutrient Sources

Surface soil samples (0–8 cm depth) were collected with a soil probe from each transport plot and from the immediate area surrounding the release plots. The samples were sieved (2 mm), and stored before analysis. Soils were analyzed for Mehlich-1 P and classified (VADCR, 1995) as low (0–6 mg kg^{-1}), medium (6–18 mg kg^{-1}), high (18–55 mg kg^{-1}), or very high (55+ mg kg^{-1}) to determine recommended manure application rates. Organic matter was analyzed using a modified Walkley–Black method and pH was determined using a 1:1 soil to distilled water ratio and solid state pH meter (Donohue and Heckendorn, 1994). Soil samples were collected approximately 1 h before each rainfall simulation and analyzed for weight-based soil moisture content (Page et al., 1982, p. 790–791).

Because the Turkey and Dairy Farms used in this study have a history of receiving land applications of manure, they had high residual soil P levels (Table 1). Thus, the Virginia Department of Conservation and Recreation (VADCR, 1995) recommends that no additional P be applied to these pastures based on an estimated crop P removal of 10.1 kg P ha^{-1} yr^{-1} (Dean Gall, personal communication, Blacksburg, VA, 27 Sept. 2002). Since no further application of animal manure is often not a viable option for farmers, the best solution is to apply the manure at a rate slightly lower than the estimated crop uptake, or to restrict manure applications to every other or every third year. Oftentimes farm equipment used to spread manure cannot spread evenly or accurately if the application rates are below a minimum level of 24.6 kg P ha^{-1} (Dean Gall, personal communication, Blacksburg, VA, 27 Sept. 2002). Thus an application rate of 24.6 kg P ha^{-1} was selected so that crop removal will gradually reduce P concentrations in the soil. In addition, manure can still be applied to the pasture every other year or once every 3 yr, so the land will remain an option for future disposal of animal waste.

Table 1. Soil properties and vegetative cover of the three sites used in this study.

Soil	Mehlich-1 P	Soil test level†	Organic matter	Vegetation	pH (1:1 water)	Soil series	Soil moisture	Particle-size distribution Sand	Silt	Clay
	mg kg^{-1}		mg kg^{-1}				%	%	%	%
Turkey Farm Release Plots	114	very high	4.8	fescue with bluegrass, orchardgrass, and broadleaf weeds	6.7	Grosclose and Poplimento	38	33	62	5
Dairy Farm Release Plots	81	very high	4.8	fescue and bluegrass with some crabgrass, white clover, and broadleaf weeds	7.0	Berks-Grosclose Complex	30	20	68	12
Tech Research Farm Release Plots	9	medium	3.4	fescue with orchardgrass and plantain	5.6	Grosclose and Poplimento	26	38	54	8
Tech Research Farm Transport Plots	9	medium	3.4	fescue and red clover	5.6	Grosclose and Poplimento	21	34	61	5

† VADCR, 1995.

The manure characteristics and land application rates are presented in Table 2. Manure samples were collected before land application and analyzed by the Clemson Agricultural Service Laboratory. Water-soluble P was determined in all manure and litter sources by the method proposed by Sharpley and Moyer (2000). Ammonia (NH_3)–N was determined using a distillation procedure (Peters et al., 2003). Nitrate (NO_3)–N in liquid dairy manure was determined using standard water procedures (EPA 353.1) and in solids by specific ion electrode (Orion 93-07). Solids were ground and dried before analyzing N with a combustion analyzer. Nitrate–N and NH_3 were subtracted from the combustion N and reported as organic N. Fresh liquid dairy manure samples were analyzed by Kjeldahl digestion. Ammonia was subtracted to report the organic N. Total N (TN) was estimated by summing NH_3, NO_3, and organic N. The pH of the manures was measured potentiometrically. Liquid dairy manure was undiluted while solids were measured in 1:2 manure/water slurry (Peters et al., 2003).

The Virginia Tech Dairy manages dietary P levels to reduce P concentrations in manure (Zhengxia et al., 2002), allowing a larger volume of manure to be applied to crop and pastureland. Typical water-soluble P concentrations are 2.41 kg 1000 L^{-1} (VADCR, 1995) in liquid dairy manure and 5.15 g kg^{-1} (Barker et al., 1990) in scraped dairy manure (which was used to form the cowpies). Wastes used in this study had lower P concentrations (Table 2), resulting in a higher N/P ratio as compared with typical wastes; thus increasing N applications to crops and pasture. Because of the variable N/P ratios of the source manure used in this study, the N application rates varied greatly between the three treatments. VADCR (1995) recommends that up to 135 kg ha^{-1} available N may be applied to pastures with orchardgrass (*Dactylis glomerata* L.), fescue, and clover (*Trifolium* spp.) when organic nutrient sources are used. Because only about 50% of total N is usually considered available, none of the treatments supplied the recommended available N application rates (Table 2).

The dried turkey litter, comprised of pine shavings and manure, was collected after a flock of turkeys were sent to market. The litter was stacked under a covered shed between 3 and 6 wk before it was applied to the plots. The litter was uniformly broadcast onto the plots. The liquid dairy manure was pumped from the Virginia Tech Dairy manure storage pond after agitation to suspend the solids. It was stored in a tank throughout the duration of the experiment, resuspended before each rainfall simulation, and poured from buckets evenly over the plots. "Standard" cowpies were constructed from fresh dairy cow deposits scraped from dairy stalls. The standard cowpies were formed by taking fresh manure and mixing it in a cement mixer for 15 min then placing it in a 20.3 cm (8 in) diam. 2.54 cm (1 in) deep mold until a weight of 0.9 kg (2.0 lb) was reached (Thelin and Gifford, 1983). A total of 360 cowpies, which covered approximately 10% of the plot surface area, were randomly positioned in the two transport plots and three cowpies were applied to each of the release plots. The high concentration of cowpies used in this study represented an area near water troughs, gates, fence lines, shady areas or bedding areas, where cattle (*Bos taurus*) tend to congregate.

Rainfall Simulation

A Tlaloc 3000 portable rainfall simulator, based on the design of Miller (1987), with a ½50WSQ Tee Jet nozzle (Spraying Systems Co., Wheaton, IL) was used to apply rain to the release plots. The nozzle was placed in the center of the simulator at 3.05 m (10 ft) above the surface of the plots and a pressure regulator was used to establish a water flow rate of 210 mL s^{-1} at the nozzle. Rainfall simulations were conducted within 24 h of the manure application to represent a condition where rainfall occurs immediately after land application of waste. Simulated rain was applied until 30 min after the initiation of runoff, as recommended by the National Phosphorus Research Project (2004). After 30 min of runoff, the rainfall simulation ended. The sample was mixed and a single grab sample was collected from the total runoff volume. The average rainfall uniformity coefficient (Schwab et al., 1993) for all rainfall simulations was 91.9%.

The Biological Systems Engineering's rainfall simulator (Dillaha et al., 1988) was used to generate storm events to produce runoff from the transport plots. Rainfall was applied at a uniform rate of 44.5 mm h^{-1} to all pasture plots and rain was applied to the entire plot areas. Two rainfall simulations were conducted within 24 h after manure application. The first simulation (S1) lasted approximately 3 h. Because initially the soils were not saturated and moisture contents varied (Table 1), the rainfall continued until a steady-state runoff resulted. The S1 simulation represented the nutrient transport during dry field conditions. Before the second simulation (S2) began (22 h after the end of S1), soils were near-saturation due to the long simulated rainfall event during S1 and an overnight rainfall which did not produce additional runoff. S2, which lasted 1 h, represented the nutrient transport characteristics under very wet soil conditions (28.6% soil moisture content) with very high potential for producing runoff. No additional manure was reapplied to the plots before the S2 simulation. The rainfall application uniformity coefficients were 93 and 96% during S1 and S2, respectively.

Sampling and Data Analysis

A single grab sample was taken during each simulation from the total runoff volume collected from each of the release plots. Grab samples of runoff were collected from the transport plots every 3 to 9 min during both simulated storm events, with more frequent collections at the beginning and end of the runoff hydrograph to better capture any changes in TSS or nutrient concentrations brought about by rapid changes in runoff rate and volume. A total of 68 samples were collected during S1 and 68 samples were collected during S2 from all eight plots. FW-1 stage recorders (chart 5-1940-AB, Belfort Instrument Co., Baltimore, MD) were used to track runoff hydrographs and record the sampling time. Each grab sample was analyzed after collection, for TSS, P, and N concentrations in runoff and flow-weighted concentrations were calculated before statistical analysis. The nutrient analysis was performed using the Bran + Luebbe (distributed by SEAL Analytical Ltd, West Sussex, UK) Traacs 800 Continuous Flow Wet Chemistry Autoanalyzer. The nutrient analysis (Clesceri et al.,

Table 2. Properties of manure and the nutrient application rates used in this study.

Manure	Moisture content	pH	Water-soluble P conc. in manure	Water-soluble P	NH_3	NO_3	Organic N	Total N	Manure application rate
	%			application rate, kg ha^{-1}					
Liquid dairy manure	96	7.8	0.30 kg 1000 L^{-1}	24.6	53	4.1	90	146	82 000 L ha^{-1}
Cowpie	83	6.4	0.75 g kg^{-1}	22.0	27	1.5	124	152	29 400 kg ha^{-1}
Turkey litter	49	8.4	8.8 g kg^{-1}	24.1	22	0.5	33	65	2 800 kg ha^{-1}

1998) included NH_3 (EPA 350.1), nitrate–nitrite (NO_3–NO_2) (EPA 353.1), ortho-phosphate (0.45 μm polyethersulfone filter, Pall Life Sciences, Ann Arbor, MI, EPA 365.1), TP (EPA365.4), TKN (EPA 351.2), and TSS (EPA 160.2). Nitrate–nitrite, NH_3, and ortho-phosphate were analyzed within 48 h of sample collection. Samples were then acidified by adding H_2SO_4 until pH < 2 and stored up to 28 d before analysis. The PP was calculated as the difference between DP and TP.

Treatments were assigned to release plots in a generalized randomized block design (Hinkelman and Kempthorne, 1994) and statistical analysis of data was performed using the Statistical Analysis System (SAS Institute, 2004). The null hypothesis was that there is no difference in the runoff, TSS, or nutrient concentrations in surface runoff among the treatments. Least square means for runoff, TSS, and nutrient concentrations between the three sites were compared using Tukey's pairwise comparison (Ott and Longnecker, 2001). Runoff, TSS, and nutrient concentrations were modeled as a function of site and treatments using analysis of variance. Runoff was tested as a covariable but all interactions were found to be insignificant.

Treatments were assigned to transport plots in a repeated measures design (Ott and Longnecker, 2001) and runoff, TSS, and nutrient concentrations were modeled as a function of treatment and simulation using analysis of variance. Runoff was again tested as a covariable but all interactions were found to be insignificant. Least square means for runoff, TSS, and nutrient concentrations between plot treatments were compared using Tukey's pairwise comparison (Ott and Longnecker, 2001). A probability level of ≤ 0.10 was considered significant.

RESULTS AND DISCUSSION

Release Plots

Table 3 presents the average time to runoff, runoff volumes, TSS concentrations, and nutrient concentrations. Differences in the onset and volume of runoff among the release plots were due to varying soil moisture conditions before the start of the rainfall simulation (Table 1) since the simulations were conducted over a 1 mo period at three different locations (Soupir, 2003). Runoff volumes were neither influenced by site nor treatment effects and the only statistical differences in runoff volume were found between the liquid dairy and turkey litter treatments at the Turkey Farm.

Total Suspended Solids Losses following Surface Application of Manure

The TSS concentrations in runoff were influenced by site effects (P value = 0.0362), and treatment effects (P value = 0.0728) which were both significant at the 0.10 probability level. Interactions between site and treatment (P value = 0.8667) were not significant. Based on P values, the differences in TSS concentrations from the plots were more influenced by site effects than the different manure treatments. The Dairy Farm and the Turkey Farm averaged 143% and 94% higher TSS concentrations in runoff than the Tech Research Farm (Table 3). Percentage organic matter, soil test P, percentage silt (Table 1) and average TSS concentrations in runoff were greater at the sites with a history of land application of animal waste. The TSS concentrations from the plots treated with cowpies were significantly higher than the control due to breakdown of the cowpies by the raindrops from the rainfall simulator.

Effects of Manures on Phosphorus Losses

Treatment effects were found to significantly influence DP, PP, and TP at the 0.001 probability level as presented in Table 4. All three treatments had significantly higher TP and DP concentrations than the control, but the concentrations were not statistically different between ma-

Table 3. Average time to start of runoff, runoff volumes, total suspended solids (TSS) concentrations, and dissolved phosphorus (DP), particulate phosphorus (PP), total phosphorus (TP), ammonia (NH_3), nitrate–nitrite (NO_3–NO_2), and total Kjeldahl nitrogen (TKN) concentrations in runoff collected from the release plots.

Manure treatment	Time to runoff	Runoff volume (SD)	TSS (SD)	DP	% of TP as DP	PP	% of TP as PP	TP (SD)	NH_3	NO_3–NO_2	TKN (SD)
	min	mL	mg L^{-1}			mg L^{-1}		mg L^{-1}			
					Tech research farm, n = 2						
Liquid dairy	21	16317a (11714)†	86a (30)	1.96a	76a	0.63a	24a	2.59a (0.69)	2.76b	1.75a	9.54a (2.6)
Cowpie	23	21255a (4859)	72a (2.0)	1.46a	53a	1.30a	47a	2.76a (0.43)	1.23ab	0.09a	13.41a (3.0)
Turkey	31	14683a (1316)	43a (18)	1.55a	74a	0.54a	26a	2.09a (1.1)	1.58ab	1.94a	6.87a (3.1)
Control	33	13480a (385)	26a (26)	0.18a	82a	0.04a	18a	0.22a (0.06)	0.17a	2.70a	2.34a (0.15)
					Dairy farm, n = 3						
Liquid dairy	7	25871a (6151)	166a (19)	1.89b	62a	1.13ab	38a	3.02ab (2.1)	2.83b	2.88a	12.62b (7.6)
Cowpie	11	21106a (2361)	189a (73)	1.51ab	35a	2.76b	65a	4.27b (1.2)	0.14a	0.11b	14.31b (3.4)
Turkey	8	29998a (1727)	135a (17)	1.96b	62a	1.22ab	38a	3.19ab (0.97)	1.86ab	2.00ab	8.65ab (4.7)
Control	10	11695a (7844)	62a (10)	0.08a	25a	0.24a	75a	0.32a (0.26)	0.03a	2.15ab	1.71a (0.73)
					Turkey farm, n = 3						
Liquid dairy	17	24857a (14660)	111a (45)	2.02b	60a	1.36a	40a	3.38a (1.2)	3.93b	3.05a	10.55a (5.7)
Cowpie	35	4077ab (16455)	131a (2.0)	0.79ab	34a	1.54a	66a	2.33a (1.6)	0.61a	0.86b	9.73a (5.1)
Turkey	35	4077b (1234)	147a (175)	0.26a	45a	0.31a	55a	0.56a (0.50)	0.15a	3.00a	2.71a (1.1)
Control	31	18321ab (4512)	52a (31)	0.23a	37a	0.38a	63a	0.61a (0.28)	0.11a	2.98a	1.47a (0.22)
					Avg. of all farms, n = 8						
Liquid Dairy	15	22348a (8626)	121ab (45)	1.96b	65b	1.04b	35b	3.00b (1.4)	3.18c	2.56a	10.90bc (5.4)
Cowpie	23	15479a (9284)	131b (63)	1.25b	40a	1.87c	60a	3.12b (1.4)	0.66ab	0.35b	12.49b (4.1)
Turkey	25	16253a (12076)	108ab (105)	1.26b	65b	0.69ab	35b	1.95b (1.4)	1.20b	2.31a	6.08ac (4.0)
Control	25	14499a (5861)	47a (25)	0.16a	42ab	0.22a	58ab	0.38a (0.27)	0.10a	2.61a	1.84a (0.55)

† In each column, means associated with each farm and followed by the same letter do not differ at the 10% level of significance according to Tukey's pairwise comparison. Standard deviations (SD) are in parentheses.

Table 4. Analysis of variance for nutrient concentrations in runoff from the release and transport plots as affected by site, treatment, and simulation.

	P value					
	Particulate P	Dissolved P	Total P	NH_3	NO_3–NO_2	Total Kjeldahl N
Release Plots						
Site	0.0531	0.0993	0.1022	0.7309	0.0585	0.1771
Treatment	0.0004	0.0001	0.0003	<0.0001	<0.0001	0.0002
Site × treatment interactions	0.3380	0.1882	0.2211	0.0380	0.8041	0.8633
Transport plots						
Treatment	0.0583	0.1137	0.1225	0.1390	0.0075	0.0751
Rainfall simulation	0.0733	0.0530	0.0526	0.7001	0.0130	0.3436
Treatment × simulation interactions	0.3057	0.2777	0.5638	0.3452	0.0346	0.9044

nure treatments. Sixty-five percent of TP was in the form of DP in runoff from plots amended with liquid dairy manure and turkey litter but the corresponding value from the plots treated with cowpies was 40% (Table 3). We attribute the partitioning of TP between the dissolved and particulate forms to the amount and form of organic matter applied to the plots. The dairy manure was applied as a liquid, which was infiltrated into the soil, and had fewer organic matter particles available for P attachment than the cowpie treatment. The turkey litter plots also received a lower application of organic matter than the cowpie plots because the litter had the highest source phosphate concentration among the different treatments (Table 2), which resulted in a lower total mass application rate.

The PP concentrations were highest from plots treated with cowpies, followed by the liquid dairy and turkey litter treatments. Because the release plots received rain within 12 to 24 h after land application of manure on the soil surface with no disturbance, there might not have been sufficient time for the phosphate applied to the plots to become stabilized and fixed by soil particles. The PP released from the plots was attached to either the organic matter applied to the plots, organic matter present on the plots from previous manure applications, or to eroding soil. Overall, the cowpie treatment and liquid dairy treatments both had significantly higher PP concentrations than the control. About 60% of the TP concentration released from the cowpie treatment was in particulate form (PP), compared with 35% from the liquid dairy and turkey litter treatments (Table 3).

Effects of Land-Use History on Phosphorus Losses

Site effects were found to be significant at the 0.1 probability level for the PP and DP concentrations in runoff (Table 4), but were not significant for TP concentrations. In runoff from the Tech Research Farm control plots, 18% of the TP was in PP form, while the corresponding values from the Turkey Farm control plots and the Dairy Farm control plots were 63 and 75%, respectively. These results indicate that a larger portion of the TP in runoff was in the particulate form from soils which have received previous manure applications. Previous manure applications resulted in very high background soil test P (Table 1), higher organic matter content, and the buildup of easily transportable residual manure particles on the soil surface. Sites receiving previous manure applications also had higher TSS concentrations in runoff and thus more particles available for nutrient transport. Previous studies have also found increased P concentrations in runoff from soils with higher soil P concentrations (Sharpley, 1995; Pote et al., 1996; Kleinman et al., 2002).

Effects of Phosphorus-Based Application Rates on Nitrogen Losses

Treatment effects were found to influence the NH_3, NO_3–NO_2, and TKN (Table 4) concentrations in runoff at the 0.001 probability level. Site effects did not significantly impact the concentrations of N released from the plots except NO_3–NO_2 at the 0.1 probability level. Apparently, N from previous manure applications had been used by the plants, leached through the soil profile, or volatilized into the atmosphere.

In this study, NO_3 was applied to the liquid dairy plots at an application rate 8.2 times higher than the turkey litter plots and 2.7 times higher than the cowpie plots. Although nitrate concentrations in the manures varied, the average NO_3–NO_2 concentration in runoff from the farms (Table 3) was very similar among the control, liquid dairy, and turkey litter treatments. We believe that most of the nitrate in the animal manure leached through the soil before runoff during the rainfall simulations. Simulated rainwater applied to the release plots had a NO_3–NO_2 concentration of 2.95 mg L^{-1}; comparable to the concentrations in runoff from these plots. A mass balance was performed comparing the amount of nitrate applied to the plots in the rainwater and the nitrate applied to the plots in the manures. The rainwater to manure NO_3 ratio was 1.46 for the liquid dairy manure treatment, 4.86 for the cowpie treatment and 9.52 for the turkey litter treatment. It is possible that the NO_3 concentrations in runoff were masked by the high NO_3 concentration in the simulation water. The cowpie plots had significantly lower NO_3–NO_2 concentrations than the other treatments.

The TKN consists of both the NH_3 and organic N derived from animal or plant material. The TKN concentration in simulated rainwater was 0.31 mg L^{-1}. The TKN concentrations released from the plots treated with cowpies and liquid dairy manure were significantly higher than those from the control. The cowpie treatment average TKN concentrations that were significantly higher than the turkey litter treatment, likely due to the higher application rate (Table 2). Because the manure was applied to the plots based on phosphate concentrations, TKN concentrations applied to and released from the plots varied.

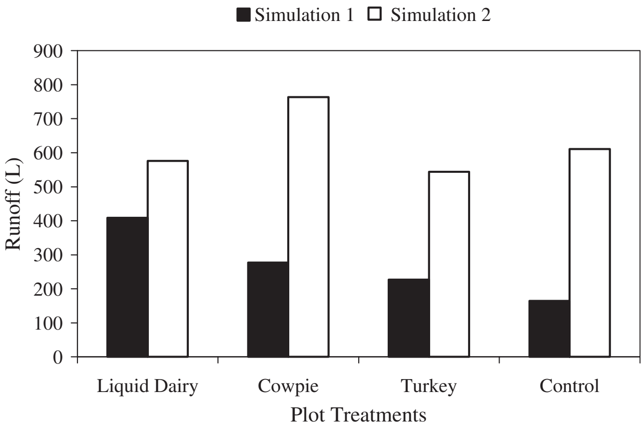

Fig. 1. Average runoff volume measured from the transport plots (n = 2). Runoff volumes were not significantly different among treatments during simulation 1 (S1) or simulation 2 (S2), but the runoff volume increase between S1 and S2 was statistically significant.

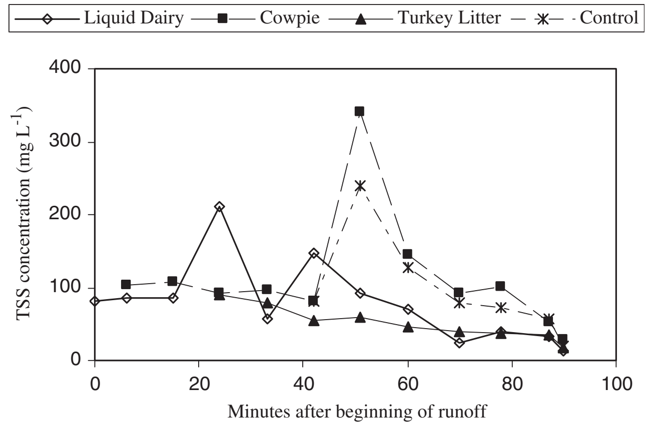

Fig. 2. Average total suspended solids (TSS) concentrations in runoff during Simulation 1 following P-based surface application of liquid dairy manure, cowpies, and turkey litter.

Transport Plots

No statistically significant differences in runoff volumes were detected among the treatments during the initial simulation (S1) and the second simulation (S2) at the 0.10 probability level. Figure 1 shows the average runoff volume measured from each of the transport plots. The runoff volume increase between S1 and S2 was statistically significant (P value < 0.10). Runoff volume increased during S2 due to the wet soil conditions from S1. The runoff volume varied among the plots due to differing initial soil moisture conditions and the wetting effects of manure treatments before the rainfall simulation (S1). The liquid dairy manure increased the moisture content of the plots before the rainfall simulation due to the nature of the waste. This may have accounted for the trend toward increased runoff volume from the liquid dairy plots during S1. Runoff volume effects on TSS and nutrient concentrations were not significant when analyzed as a co-variable. Because the differences in runoff volume appear to be quite large (Fig. 1), additional replications of each treatment might have resulted in more statistically significant differences between treatment responses.

Total Suspended Solid Losses from the Edge of the Field

Flow-weighted concentrations were calculated for the TSS in runoff from each of the transport plots (Table 5). With the limited number of treatment replications available in this study, mean TSS concentrations were not statistically different between the two simulations or among any treatments, but there were some interesting trends. For example, mean TSS concentration in runoff from the cowpie treatment was more than double the mean from any other treatment during S1, while liquid dairy manure produced the highest mean TSS concentration during S2, but these differences were not statistically significant.

The cowpies were easily dispersed by raindrops, and readily carried off the plots by runoff, resulting in higher TSS concentrations (Fig. 2). This process was visually observed, although the TSS concentrations from the plots treated with cowpies were not statistically higher than the other treatments during S1. The flow-weighted TSS concentration decreased during S2 for all treatments, except for the liquid dairy manure, compared with S1. During S2 much of the transportable organic materials might already have been washed off the cowpie and turkey litter plots, which would reduce TSS concentrations.

Effects of Manures on Edge-of-Field Phosphorus Concentrations

Overall treatment effects were not significant for DP or TP but were significant for PP at the 0.1 significance level (Table 4). The DP concentrations in runoff from the turkey litter treatment were 39% greater than the average concentration from the liquid dairy treatment,

Table 5. Flow-weighted concentrations of total suspended solids, dissolved phosphorus (DP), particulate phosphorus (PP), and total phosphorus (TP) in runoff from the transport plots during simulation 1 (S1) and simulation 2 (S2).

	Total suspended solids		Dissolved P				Particulate P				Total P		
Treatment	S1	S2	S1	S2	Avg.	% of TP as DP	S1	S2	Avg.	% of TP as PP	S1	S2	Avg.
	mg L^{-1}						mg L^{-1}				mg L^{-1}		
Liquid dairy	**59.3**	**83.6**	**0.95**	**0.55**	**0.75ab†**	**85% a**	**0.14**	**0.12**	**0.13a**	**15% a**	**1.09**	**0.66**	**0.88a**
Cowpie	**177.2**	**54.8**	**0.89**	**0.78**	**0.84ab**	**54% ab**	**0.82**	**0.64**	**0.73a**	**46% ab**	**1.72**	**1.42**	**1.57a**
Turkey	**37.3**	**22.5**	**1.55**	**0.90**	**1.22a**	**87% a**	**0.19**	**0.18**	**0.18a**	**13% a**	**1.74**	**1.08**	**1.41a**
Control	**85.1**	**29.0**	**0.05**	**0.05**	**0.05b**	**36% b**	**0.14**	**0.05**	**0.09a**	**64% b**	**0.19**	**0.10**	**0.14a**

† In each column, means followed by the same letter (or no letter) do not differ at the 10% level of significance according to Tukey's pairwise comparison.

31% greater than the average concentration from the cowpie treatment, and significantly higher (according to Tukey's pairwise comparison) than the control treatment (Table 5). Even though the turkey litter was applied at a lower application rate (2800 kg ha^{-1}) than the other manure treatments, the higher concentration of phosphate in the source manure (Table 2) and the availability of soluble P at the soil surface (Kleinman et al., 2002) resulted in higher concentrations of DP in runoff. In this study, dietary P management resulted in dairy manures with lower soluble P concentrations, but P-based management strategies allowed for equal applications of soluble P to the plots. Lower concentrations of DP in runoff from plots treated with dairy manures was not observed from the release plots, possibly because of the short distance between the applied manure and sample collection. The transport plots allowed for an overland flow event to occur and represent the concentrations that might flow into surface waters.

Similar to observations from the release plots, the majority of the TP was in the form of DP from the plots receiving liquid dairy and turkey litter treatments. The DP in runoff from the plots treated with turkey litter accounted for 87% of the TP, while the corresponding value from plots amended with liquid dairy manure was 85%. The high percentage of DP in runoff could be attributed to the amount and form of organic matter in the manures applied to the plots. Previous studies have also found that P in runoff from pastures is often predominately in the form of DP (Edwards and Daniel, 1993; Sauer et al., 2000); therefore, management practices should focus on reducing the transport of DP from pastureland treated with liquid dairy manure or turkey litter.

Because the Tech Research Farm had low residual soil P concentrations and no history of previous manure applications, it is believed that the PP present in runoff was mainly attached to the organic matter in the animal waste applied to the plots that was washed away by runoff. The cowpie treatment had the highest concentrations of PP in runoff during both simulations followed by the turkey litter and liquid dairy treatments; however, these differences were not significant according to the Tukey's pairwise comparison. The average concentration of TP in runoff from the two rainfall simulations was also highest from plots treated with cowpies, although no significant differences were detected among the treatments. The concentration in runoff from the cowpie treatment was 11% higher than the concentrations in runoff from the turkey litter treatment (1.41 mg L^{-1}) and 78% higher than the concentrations in runoff from the liquid dairy manure (0.88 mg L^{-1}). The cowpie treatment had the highest concentrations because it contributed similar concentrations of PP (46% of TP) and DP (54% of TP) to runoff.

Effects of Manures on Edge-of-Field Phosphorus Losses

The soluble P application rate to all of the plots was similar, which resulted in comparable mass loadings among the treatments when the total yield during S1 and S2 was combined. The cowpie treatment had the greatest mass transport rate, with a total of 0.31% of the applied soluble P lost during the two rainfall simulations, followed by the turkey litter treatment (0.28%) and liquid dairy manure treatment (0.26%); however, differences among the treatments were not statistically significant. Because the treatments were applied to pasturelands, the grass assisted in retaining the nutrients and reducing their transport. Overall, $<0.8\%$ of the source soluble P was present in the form of PO_4 in runoff from the release plots (data not shown), and $<0.31\%$ was transported by runoff from the transport plots. The cumulative loads during S1 and S2 are presented in Fig. 3. Although no statistical differences were found between runoff volumes from various treatments (Fig. 1), differences in mass loading were influenced by the slight variation in runoff volumes between the treatments. During S1, the DP yield was greatest from the plots amended with liquid dairy manure (Fig. 3), primarily due to the high moisture content of the manure which resulted in a greater runoff volume (Fig. 1) than the other treatments. The turkey litter treatment had the highest DP concentration in runoff during S1 and S2 (Table 5), but the low moisture content of the litter reduced runoff volumes and thus mass yields. During S2 the cowpie plots produced a greater runoff volume, resulting in the highest mass loading even though the plots treated with turkey litter had higher concentrations. The TP yields were also influenced by runoff volume during S1; however, during S2 the cowpie treatment yielded the greatest runoff volume and concentrations among the treatments.

A field can potentially contribute to increased eutrophication of downstream water bodies with P yields <1 to 2 kg ha^{-1} yr^{-1} (Hansen et al., 2002). The combined yield during S1 and S2 from these plots ranged from 0.16 to 0.29 kg ha^{-1}(Fig. 3). Using the results of this study, the annual TP yield from the cowpie treatment was estimated to be 0.76 kg ha^{-1} yr^{-1} using average runoff volumes from a small agricultural watershed in the Piedmont Region of Virginia (Mostaghimi et al., 1997) and assuming that cattle congregate near streams year-round. Liquid dairy manure and poultry litter are typically applied to pasturelands twice per year and yields would be much lower from runoff events occurring between applications; so an attempt was not made to extrapolate the yields obtained from these plots to annual values.

Effects of Manures on Edge-of-Field Nitrogen Losses

The NH_3, NO_3, and TKN flow-weighted concentrations are presented in Table 6. Treatment effects, simulation effects, and treatment × simulation interactions (Table 4) all significantly influenced NO_3–NO_2 concentrations in runoff at the 0.1 probability level. Nitrate comprised a small portion of the TN in the manures (3% of liquid dairy TN and $<1\%$ of cowpie and turkey litter TN). Similar to observations from the release plots,

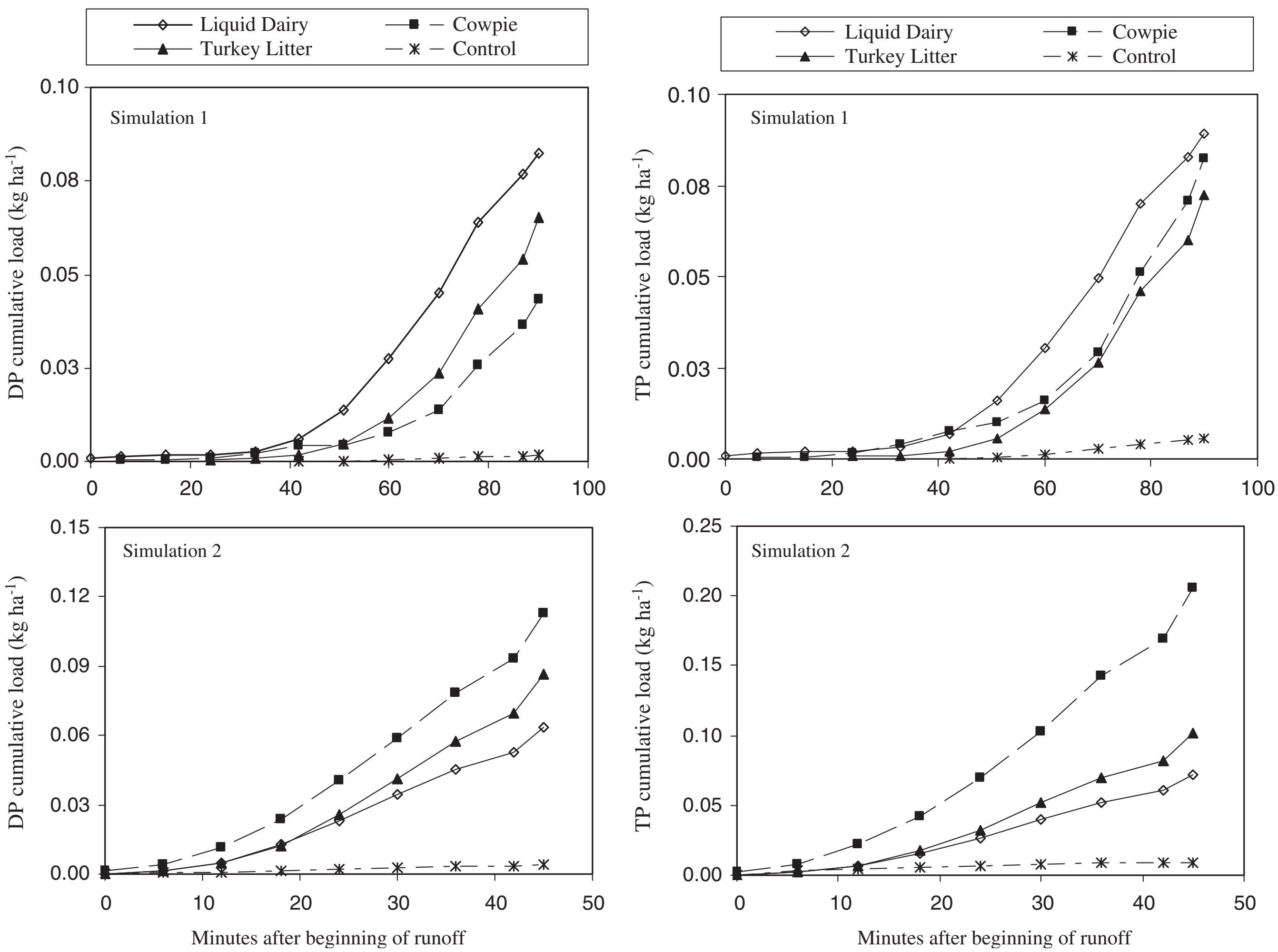

Fig. 3. Dissolved phosphorus (DP) and total phosphorus (TP) cumulative mass loads during Simulation 1 and Simulation 2 following P-based surface application of liquid dairy manure, cowpies, and turkey litter.

there was very little difference between the average concentrations of NO_3 in runoff from the plots treated with turkey litter (0.9 mg L^{-1}) and liquid dairy manure (0.8 mg L^{-1}), even though eight times more NO_3 was applied to the plots treated with liquid dairy manure (Table 2). The NO_3–NO_2 concentrations in runoff from the control, liquid dairy, and turkey litter treatments were similar to the average NO_3–NO_2 concentration in rainwater (average 0.64 mg L^{-1} during S1 and S2). Because the NO_3 comprised such a small proportion of the TN, it is possible that the NO_3–NO_2 in the animal waste infiltrated the soil during the rainfall simulation and the observed concentrations are mostly due to rainwater. The cowpie treatment had statistically lower NO_3 concentrations in runoff than all other treatments.

The average NH_3 concentration in runoff was highest from the plots treated with cowpies; however, there were no statistical differences among the treatments. Treatment and simulation effects were also not significant at the 0.1 probability level (Table 4). Since the NH_3 was applied to the liquid dairy plots at twice the application rate of the other treatments (Table 2), these results indicate that NH_3 is more transportable from cowpies than the other waste types. Ammonia only comprised 17% of the TN in the cowpie, compared to 35% of the liquid dairy treatment and 34%

Table 6. Flow-weighted concentrations of nitrate–nitrite (NO_3–NO_2), ammonia (NH_3), and total Kjeldahl nitrogen (TKN) in runoff from the transport plots during simulation 1 (S1) and simulation 2 (S2).

	NH_3			NO_3–NO_2			TKN		
Treatment	S1	S2	Avg.	S1	S2	Avg.	S1	S2	Avg.
	mg L^{-1}								
Liquid dairy	0.97	0.74	0.9a†	0.65	1.02	0.8b	2.60	1.82	2.2a
Cowpie	1.64	2.02	1.8a	0.21	0.03	0.1a	10.36	9.06	9.7a
Turkey	1.44	1.08	1.3a	0.73	1.02	0.9b	2.50	1.98	2.2a
Control	0.18	0.18	0.2a	0.57	0.81	0.7b	1.63	1.59	1.6a

† Values followed by the same letter in each column do not differ at the 10% level of significance according to Tukey's pairwise comparison.

of the turkey litter treatment. We believe the NH_3 volatilized from the plots amended with liquid dairy manure and turkey litter, whereas the cowpies had less surface area exposed to the atmosphere, and therefore less volatilization.

The TKN concentration in runoff from the transport plots was highest from the plots treated with cowpies, although no significant differences were detected among the treatments (Table 6). The concentration of TKN in runoff from the plots treated with cowpies was 9.7 mg L^{-1}; 4.4 times higher than the values from the liquid dairy or turkey litter treatments. Rainwater applied to the transport plots had an average TKN concentration of 1.9 mg L^{-1} during S1 and S2 and probably contributed to the TKN concentrations in runoff. Of the three treatments investigated, cowpies were most likely to contribute high TKN loading into surface waters. The TKN cumulative loads are presented in Fig. 4. The cowpie treatment had the greatest mass transport rate with a total of 1.2% of the applied TKN lost during both simulations. Mass losses from the turkey litter plots were 0.53% of the total TKN applied and 0.26% from plots receiving liquid dairy manure. During S1, the liquid dairy manure had greater TKN mass losses than the

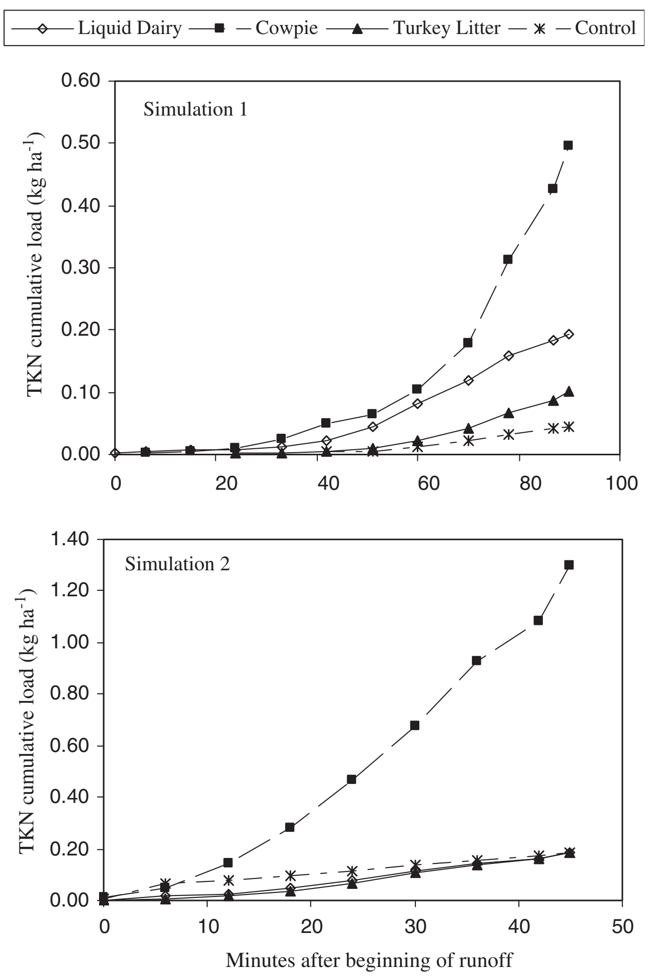

Fig. 4. Total Kjeldahl nitrogen (TKN) cumulative loads during Simulation 1 and Simulation 2 following P-based surface application of liquid dairy manure, cowpies, and turkey litter.

turkey litter treatment, even though runoff concentrations were similar. We attribute this mostly to the higher moisture content of the liquid dairy manure, which resulted in slightly higher runoff volume from the plots receiving the liquid dairy treatment.

By basing the animal waste application rates on P instead of the N requirements of the crop, the TKN concentrations in runoff were reduced compared to previous studies performed on fescue pastures. McLeod and Hegg (1984) applied dairy manure and poultry manure to fescue pasture at rates ranging from 85 to 289 kg N ha^{-1} and found TKN concentrations in runoff, 1 d following application, to be 16 mg L^{-1} from plots receiving dairy manure and 40 mg L^{-1} from plots receiving poultry manure applications. Mean TKN loss after four rainfall events was 1.8% and 3.8% of the applied manure from the dairy and poultry manure, respectively. Edwards and Daniel (1993) applied poultry litter to fescue plots at 218, 435, and 870 kg TN ha^{-1} which resulted in TKN concentrations of 159.7, 363.3, and 564.0 mg L^{-1} during a 5 cm h^{-1} simulated rainfall applied 24 h after litter application. The TKN concentrations in runoff were lower than values presented in previous studies and the liquid dairy manure and cowpie treatments did not meet the recommended available N application rate of 135 kg ha^{-1} (Table 2) for pasturelands receiving organic nutrient sources. Based on these findings, we believe there is little potential for increased N levels in runoff when excess P in dairy cow diets is reduced and P-based management practices are required. However, inorganic fertilizer may be necessary to meet N crop demands which could potentially increase the N concentrations in runoff.

CONCLUSIONS

This field study measured the transport of nutrients from livestock manure applied to pastures with and without previous history of animal waste applications, but based on P management practices. Farms with a history of manure applications had higher TSS concentrations in runoff. The turkey litter treatment had a significantly higher concentration of DP transported to the edge of the field than the control. The DP accounted for 87 and 85% of the TP in runoff from the turkey litter and liquid dairy treatments, respectively. Even with reduced dietary P levels, none of the treatments supplied the recommended available N application rates and thus, the P-based management practices did not result in increased N concentrations in runoff when compared to previous studies.

To reduce P concentrations in runoff from pasture treated with liquid dairy manure or turkey litter, the selected management practices should focus on reducing the transport of DP, even when dietary P levels in dairy cattle are lowered. Previous research has investigated methods of reducing nutrient loadings into surface waters. The high nutrient concentrations in runoff from the plots treated with cowpies imply that areas where cattle may congregate, such as shaded areas, watering or feeding areas, should be moved away from streams to increase the buffer distance between the manure and waterways. Restricting grazing cattle access to streams will reduce direct loading, but the results from this study imply that a buffer zone between grazing cattle and streams is also necessary to reduce nutrient loadings to streams. In areas with high cattle density, a detention basin could be installed to reduce the first flush effects and allow for organic particles and sediment to settle.

ACKNOWLEDGMENTS

This work was supported by the USEPA through STAR grant no. R83136801-0. Although the research described in the article has been funded in part by the USEPA STAR programs, it has not been subjected to any USEPA review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred. The authors wish to thank Jan Carr and Julie Jordan for their assistance with sample collection and analysis.

REFERENCES

Barker, J.C., J.P. Zublena, and C.R. Campbell. 1990. Livestock manure production and characterization in North Carolina. North Carolina Coop. Ext. Serv., Raleigh.

Clesceri, L.S., A.E. Greensburg, and A.D. Eaton. 1998. Standard methods for the examination of water and wastewater. United Book Press, Baltimore, MD.

Dillaha, T.A., B.B. Ross, S. Mostaghimi, C.D. Heatwole, V.O. Shanholtz, and F.B. Givens. 1988. Rainfall simulation: A tool for best management practice education. J. Soil Water Conserv. 43:288–290.

Donohue, S.J., and S.E. Heckendorn. 1994. Laboratory procedures: Virginia Tech Soil Testing and Plant Analysis Laboratory. Publ. 452-881. Virginia Coop. Ext., Blacksburg.

Edwards, D.R., and T.C. Daniel. 1993. Effects of poultry litter application rate and rainfall intensity on quality of runoff from fescuegrass plots. J. Environ. Qual. 22:361–365.

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

Eghball, B., and J.E. Gilley. 1999. Phosphorus and nitrogen in runoff following beef cattle manure or compost application. J. Environ. Qual. 28:1201–1210.

Fozzard, I., R. Doughty, R. Ferrier, T. Leatherland, and R. Owen. 1999. A quality classification for management of Scottish standing waters. Hydrobiologia 395–396:433–455.

Hansen, N.C., T.C. Daniel, A.N. Sharpley, and J.L. Lemunyon. 2002. The fate and transport of phosphorus in agricultural systems. J. Soil Water Conserv. 57:409–416.

Heathman, G.C., A.N. Sharpley, S.J. Smith, and J.S. Robinson. 1995. Land application of poultry litter and water quality in Oklahoma, U.S.A. Fert. Res. 40:165–173.

Hinkelman, K., and O. Kempthorne. 1994. Design and analysis of experiments. John Wiley, New York.

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

Kleinman, P.J.A., A.N. Sharpley, B.G. Moyer, and G.F. Elwinger. 2002. Effect of mineral and manure phosphorus sources on runoff phosphorus. J. Environ. Qual. 31:2026–2033.

Knowlton, K.F., and J.H. Herbein. 2002. Phosphorus partitioning during early lactation in dairy cows fed diets varying in phosphorus content. J. Dairy Sci. 85:1227–1236.

McLeod, R.V., and R.O. Hegg. 1984. Pasture runoff water quality from application of inorganic and organic nitrogen sources. J. Environ. Qual. 13:122–126.

Miller, W.P. 1987. A solenoid-operated, variable intensity rainfall simulator. Soil Sci. Soc. Am. J. 51:832–834.

Mostaghimi, S., S.W. Park, R.A. Cooke, and S.Y. Wang. 1997. Assessment of management alternatives on a small agricultural watershed. Water Res. 31:1867–1878.

National Phosphorus Research Project. 2004. National Phosphorus Research Project Rain Simulator Protocols. Available at www.sera17.ext.vt.edu/SERA_17_Publications.htm (accessed 15 Aug. 2005; verified 12 Apr. 2006).

Ott, R.L., and M. Longnecker. 2001. An introduction to statistical methods and data analysis. Thomas Learning, Pacific Grove, CA.

Page, A.L., R.H. Miller, and D.R. Keeney. 1982. Methods of soil analysis. Part 2. 2nd ed. ASA and SSSA, Madison, WI.

Peters, J., S.M. Combs, B. Hoskins, J. Jarman, J.L. Kovar, M.E. Watson, A.M. Wolf, and N. Wolf. 2003. Recommended methods of manure analysis. Coop. Ext. Publ. Operations, Madison, WI.

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

Powell, J.M., Z. Wu, and L.D. Satter. 2001. Dairy diet effects on phosphorus cycles of cropland. J. Soil Water Conserv. 56:22–26.

Ross, I.J., S. Sizemore, J.P. Bowden, and C.T. Hann. 1978. Effects of soil injection of liquid dairy manure on the quality of surface runoff. Res. Rep. 113. Univ. of Kentucky Water Resource Res. Inst., Lexington.

SAS Institute. 2004. Version 9.1. SAS Inst., Cary, NC.

Sauer, T.J., T.C. Daniel, D.J. Nichols, C.P. West, P.A. Moore, Jr., and G.L. Wheeler. 2000. Runoff water quality from poultry litter-treated pasture and forest sites. J. Environ. Qual. 29:515–521.

Schwab, G.O., D.D. Fangmeier, W.J. Elliot, and R.K. Frevert. 1993. Soil and water conservation engineering. 4th ed. John Wiley & Sons, New York.

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

Sharpley, A.N., S.C. Chapra, R. Wedepohl, J.T. Sims, T.C. Daniel, and K.R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 23:437–451.

Sharpley, A.N., T.C. Daniel, and D.R. Edwards. 1993. Phosphorus movement in the landscape. J. Prod. Agric. 6:492–500.

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

Sims, J.T. 2000. The role of soil testing in environmental risk assessment for phosphorus. p. 57–81. *In* A.N. Sharpley (ed.) Agriculture and phosphorus management: The Chesapeake Bay. Lewis Publ., Boca Raton, FL.

Soupir, M.L. 2003. Release and transport of bacteria and nutrients from livestock manure applied to pasturelands. M.S. thesis. Virginia Polytechnic Inst. and State Univ., Blacksburg.

Tabbara, H. 2003. Phosphorus loss to runoff water twenty-four hours after application of liquid swine manure or fertilizer. J. Environ. Qual. 32:1044–1052.

Tarkalson, D.D., and R.L. Mikkelsen. 2004. Runoff phosphorus losses as related to phosphorus source, application method, and application rate on a piedmont soil. J. Environ. Qual. 33:1424–1430.

Thelin, R., and G.F. Gifford. 1983. Fecal coliform release patterns from fecal material of cattle. J. Environ. Qual. 12:57–63.

Virginia Department of Conservation and Recreation Standards and Criteria. 1995. Virginia nutrient management standards and criteria. Virginia Div. of Soil and Water Conserv., Richmond.

Wu, Z., L.D. Satter, and R. Sojo. 2000. Milk production, reproductive performance, and fecal excretion of phosphorus by dairy cows fed three amounts of phosphorus. J. Dairy Sci. 85:1028–1041.

Zhengxia, D., K.F. Knowlton, R.A. Kohn, Z. Wu, L.D. Satter, G. Zhang, J.D. Toth, and J.D. Ferguson. 2002. Phosphorus characteristics of dairy feces affected by diets. J. Environ. Qual. 31:2058–2065.