

Repeated Compost Application Effects on Phosphorus Runoff in the Virginia Piedmont

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ABSTRACT

Increasing amounts of animal and municipal wastes are being composted before land application to improve handling and spreading characteristics, and to reduce odor and disease incidence. Repeated applications of composted biosolids and manure to cropland may increase the risk for P enrichment of agricultural runoff. We conducted field research in 2003 and 2004 on a Fauquier silty clay loam (Ultic Hapludalfs) to compare the effects of annual (since 1999) applications of composted and uncomposted organic residuals on P runoff characteristics. Biosolids compost (BSC), poultry litter-yard waste compost (PLC), and uncomposted poultry litter (PL) were applied based on estimated plant-available N. A commercial fertilizer treatment (CF) and an unamended control treatment (CTL) were also included. Corn (*Zea mays* L.) and a cereal rye (*Secale cereal* L.) cover crop were planted each year. We applied simulated rainfall in fall 2004 and analyzed runoff for dissolved reactive P (DRP), total dissolved P (TDP), total P (TP), total organic C (TOC), and total suspended solids (TSS). End of season soil samples were analyzed for Mehlich-3 P (M3P), EPA 3050 P (3050P), water soluble P (WSP), degree of P saturation (DPS), soil C, and bulk density. Compost treatments significantly increased soil C, decreased bulk density, and increased M3P, 3050P, WSP, and DPS. The concentration of DRP, TDP, and TP in runoff was highest in compost treatments, but the mass of DRP and TDP was not different among treatments because infiltration was higher and runoff lower in compost-amended soil. Improved soil physical properties associated with poultry litter-yard waste compost application decreased loss of TP and TSS.

INCREASING AMOUNTS of animal manure and municipal wastes (biosolids) are being applied to agricultural land as sources of nutrients and organic matter and because land application is a low cost disposal method. Repeated N-based applications of these residuals leads to an accumulation of soil P in excess of crop needs and can increase P enrichment of agricultural runoff (Sharpley et al., 1998; Sims et al., 1998). It is environmentally expedient to transport and apply these residuals to land where soils stand to benefit agronomically from P application. The high transportation cost associated with transporting wastes is the primary factor limiting their distribution (Bosch and Napit, 1992; Janzen et al., 1999); thus, manures and biosolids have typically been applied to soils at rates that supply P in excess of crop needs.

One practice that has been increasingly employed to increase manure transportation out of high density livestock and poultry production areas is composting (Simpson, 1998). Composting organic residuals improves handling and storage characteristics and may make transportation more feasible by increasing the residuals

value (Rynk, 1992; Sharpley et al., 1998). In addition, composting is increasingly employed as a treatment process for biosolids because it reduces odor and diseases in the residual. Unfortunately, composting narrows the N/P ratio in the product, which may exacerbate environmental P problems.

The ratio of plant-available N (PAN)/P in manure or biosolids compost is approximately 1:2, whereas the ratio of N/P in most crops is between 7:1 and 10:1 (Eck and Stewart, 1995; Evanylo, 1999; Preusch et al., 2002; Heckman et al., 2003; Sikora and Enkiri, 2004). The accumulation of P in amended soil is likely to occur when compost is repeatedly applied based on crop N needs.

Eghball and Gilley (1999) and Sharpley and Moyer (2000) have demonstrated that compost applied at agronomic N rates may pose a risk for elevated P in runoff; however, neither of these studies considered the long-term effects of repeated compost applications on soil physical properties, such as bulk density, aggregate stability, or water infiltration that can dramatically influence runoff. As much as 90% of P lost from agronomic land is in the particulate form when soil P levels are not excessive (Sharpley and Beegle, 1999); thus, erosion potential plays a significant role.

The beneficial effects of compost on soil tilth, the combination of soil physical properties that include aggregation, bulk density, porosity, and water-holding capacity (Khaleel et al., 1981; Aggelides and Londra, 2000; Evanylo and Sherony, 2002; Foley and Cooperband, 2002) may improve crop productivity, and minimize soil and water degradation by reducing runoff and erosion.

Agricultural producers may be encouraged to utilize compost to supplement their fertility management if compost use can be shown to be an agronomically, environmentally, and economically sound alternative to land application of uncomposted manures and biosolids. The objective of this research was to compare the effects of two types of compost (poultry litter-yard waste, biosolids-woodchips) with conventional fertilizer and uncomposted poultry litter on soil properties that influence infiltration and surface transport of N, P, and sediment.

MATERIALS AND METHODS

Treatments and Experimental Design

Field research was conducted at the Northern Piedmont Agricultural Research and Education Center (NPAREC) in

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Published in J. Environ. Qual. 35:2342–2351 (2006).

Technical Reports: Waste Management

doi:10.2134/jeq2006.0105

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Abbreviations: M1P, Mehlich-1 P; WSP, water soluble P; M3P, Mehlich-3 P; P_{ox}, acid ammonium oxalate P; DPS, degree of P saturation; 3050P, EPA 3050 P; 3050Ca, EPA 3050 Ca; 3050Fe, EPA 3050 Fe; 3050Al, EPA 3050 Al; TKN, total Kjeldahl N; PAN, plant-available N; TOC, total organic C; CCE, calcium carbonate equivalence; BSC, biosolids compost; PLC, poultry litter compost; PL, poultry litter; CF, commercial fertilizer; CTL, control; TP, total P; TDP, total dissolved P; PP, particulate P; DURP, dissolved unreactive P; DRP, dissolved reactive P; TSS, total suspended solids.

Orange, Virginia on a Fauquier silty clay loam (fine, mixed, mesic Ultic Hapludalf) having a slope of 7 to 10%. Eight treatments were established in the spring of 2000 to investigate the agronomic and environmental effects of compost use in the Virginia Piedmont. The following five treatments were selected for reporting in this study as these treatments represent a range of compost treatments, a control, and standard commercial fertilizers: (1) unamended control (CTL); (2) commercial fertilizer (CF); (3) poultry litter (PL); (4) poultry litter yard-waste compost (PLC); and (5) biosolids-woodchip compost (BSC). The CF consisted of annual application of commercial inorganic fertilizer at rates recommended by the Virginia Tech-Virginia Cooperative Extension Soil Testing Laboratory for crop N, P, and K requirements. The PL was annually applied at rates estimated to meet crop N requirements. The compost treatments established in 2000 were biannual (2000, 2002) agronomic N rates of poultry litter-yard waste compost with (2001) and without supplemental inorganic fertilizer N. The experimental design was a randomized complete block with four replications, and plot size was 3.65 by 7.60 m.

In the spring of 2003, two of the four replicates from each of the two treatments continued to receive PLC and the other two replicates from each of the two treatments received BSC. The rate at which each compost was applied in 2003 and 2004 was based on calculated agronomic N supply. This scheme enabled us to investigate the effects of recent applications of diverse compost types on soils with a history (2000 through 2002) of identical compost applications.

The Class A biosolids compost was produced by processing a mixture of anaerobically digested biosolids and woodchips using the Beltsville aerated static pile method (USEPA, 1980). The biosolids cake for the production of BSC was treated with FeCl_3 and $\text{Ca}(\text{OH})_2$ at approximately 80 and 300 g kg^{-1} (dry matter basis), respectively, as conditioning agents. The poultry litter-yard waste compost was produced using the windrow method (Rynk, 1992) with feed stocks of yard waste (largely deciduous tree leaves and ground woody waste) and broiler litter. The PL used was an uncomposted, commercially available product.

The first 3 yr of the study examined the impacts on soil and water quality and yield of the original treatments in a vegetable production system (Evanylo and Sherony, 2002). Crops grown included pumpkin (*Cucurbita pepo*; V. Magic Lantern) in 2000, sweet corn (*Zea mays*; V. Silver Queen) in 2001, and bell pepper (*Capsicum annuum*; V. Aristotle) in 2002. Cereal rye (*Secale cereal* L.) was planted in all plots in the autumn of every year as a winter cover crop. Following modification of the treatments in the spring of 2003 a crop rotation of maize (*Zea mays* L. V. Pioneer 31G20)–cereal rye was established on all treatments.

Nitrogen needs for maize were estimated to be 146 kg ha^{-1} according to the yield potential for the Fauquier silty clay loam by the Virginia Agronomic Land Use Evaluation System (Simpson et al., 1993). Phosphorus and K requirements were determined by VCE soil test recommendations (Donohue and Heckendorn, 1994). Ammonium nitrate (33–0–0), triple superphosphate (0–46–0) and muriate of potash (0–0–60) were used to supply N, P, and K, respectively. The lime requirements were determined by the Adams-Evans single buffer method (Sims, 1996).

Plant-available N in compost and poultry litter was estimated by adding 100% of the measured $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ and the fraction of organic N estimated to be mineralizable during the first season. Mineralization coefficients used were 0.1 for compost and 0.6 for poultry litter (Evanylo, 1994; Department of Conservation and Recreation, 2002). Amendments were applied and immediately roto-tilled 15 cm into the soil. In 2003 and 2004 maize was planted within 2 d of amendment application and thinned to approximately 52 000 plants ha^{-1}

3 wk after emergence. Weed control was accomplished with appropriate herbicides and hand weeding as necessary.

Sampling and Analysis

Organic Amendment Characterization

The organic amendments were sampled at application and analyzed by A&L Eastern Laboratories (Richmond, Virginia) within 48 h for total Kjeldahl N (TKN-N) by USEPA 351.3 (USEPA, 1979), $\text{NH}_4\text{-N}$ by EPA 350.2 (USEPA, 1979), $\text{NO}_3\text{-N}$ by SM 4500-NO3F (AWWA, 1998), TOC by USEPA 415.1 (USEPA, 1999), and TP by USEPA 3052 (USEPA, 1999). Additional samples collected at application were oven-dried (60°C), ground to pass a 0.85-mm screen in a stainless steel Wiley mill, and analyzed for (i) water soluble P, Al, Fe, and Ca (WSP, WSAI, WSFe, WSCa, respectively); (ii) Mehlich-3 extractable P, Al, Fe, and Ca (M3P, M3Al, M3Fe, and M3Ca, respectively); and (iii) USEPA 3050B extractable P, Al, Fe, and Ca (3050P, 3050Al, 3050Fe, 3050Ca, respectively). The WSP, WSAI, WSFe, and WSCa were extracted during a 2-hr reaction time using a 1:10 ratio of analyte/deionized water (Self-Davis and Moore, 2000). Mehlich-3 P, M3Al, M3Fe, and M3Ca were extracted during a 5-min reaction time using a 1:10 ratio of analyte/0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0.001 M EDTA (Mehlich, 1984). The USEPA 3050B employed an acid peroxide digestion (USEPA, 1986). Calcium carbonate equivalence (CCE) was determined on all amendments by AOAC 955.01 (AOAC, 2000). All P extractions, digestions and CCE were conducted in quadruplicate.

Soil Assays

Soil was sampled to a depth of 15 cm in the fall of each year following crop harvest. Soil samples were analyzed for pH and Mehlich-1 P, K, Ca, Mg, Mn, and Zn by the Virginia Tech Soil Testing Laboratory (Donohue and Friedericks, 1984); for M3P (Mehlich, 1984); WSP (Self-Davis et al., 2000); 3050P (USEPA, 1986); and acid ammonium oxalate extractable P, Fe, and Al (P_{ox} , Fe_{ox} , Al_{ox} ; 1:40 soil/0.2 M acid ammonium oxalate [pH 3], 2-h reaction time in the dark; McKeague and Day, 1966).

The concept of the degree of P saturation (DPS) has been used as a tool to determine the status of a soil's P binding capacity (van der Zee and van Riemsdijk, 1988). The DPS, as defined by Eq. [1] is

$$\text{DPS} (\%) = \left(\frac{\text{P}_{\text{ox}}}{\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}}} \right) \times 100 \quad [1]$$

where P_{ox} , Al_{ox} , and Fe_{ox} are acid ammonium oxalate extractable P, Al, and Fe in mmols kg^{-1} and was calculated for soil from each treatment in this study.

Additional soil samples were collected from the 0- to 5-cm depth following the simulated rainfall event and analyzed for WSP and M3P because the shallower sampling has been shown to be a better predictor of the concentration of DRP in runoff than 0 to 15 cm (Schroeder et al., 2004). Total C was determined on soil samples collected from 0 to 15 cm using a VarioMax CNS macro elemental analyzer (Elementar Americas, Mt. Laurel, NJ). Three soil cores, 7.5 cm in diameter and 7.5 cm deep were collected from each plot for determination of bulk density (Culley, 1993).

Soil and Water Quality

Rainfall simulations were conducted in September 2004, 1 wk following corn harvest on all four replicates of the CTL,

CF, PL, PLC, and BSC treatments. Sampling events were generated using a portable rainfall simulator based on the design of Miller (1987). Water was delivered at a rate of 7.5 cm h⁻¹ to overland flow plots, 1.5 by 2 m, with the long axis oriented downslope. Steel borders were installed 5 cm below and 10 cm above ground level to contain the overland flow. Runoff water was collected from the plots for 30 min after the initiation of runoff. The volume of runoff was determined on a mass basis and a one-liter subsample was collected for analysis. A 50-mL aliquot was immediately filtered through a 0.45- μ m Millipore filter, and both filtered and unfiltered samples were stored at 4°C until analysis was conducted (approximately 72 h later).

Water samples were analyzed for TP by EPA 365.4, ortho-P by EPA 365.1, TOC by EPA 415.1, and TSS by EPA 160.2 (USEPA, 1979). Total dissolved P and DRP were determined on filtered (<0.45 μ m) samples. Phosphorus fractions in runoff water defined as dissolved unreactive phosphorus (DURP) were determined as the difference between TDP and DRP and particulate phosphorus (PP) as TP less TDP.

Data Analysis

Analysis of variance and mean separations were performed using the general linear model procedure of SAS Institute (2002). The least significant difference procedure (LSD) with a probability level of 0.05 was used to determine significant differences between treatment means. Simple linear regression analysis utilized the regression procedure of SAS.

RESULTS AND DISCUSSION

Organic Amendment Characterization

General Chemical Properties

Selected chemical properties of the organic residuals applied in 2003 and 2004 were consistent across years (Table 1). Total N (TKN + NO₃-N) was similar between both PLC and BSC and less than half of PL. Estimated PAN, ranging from 1.89 to 37.0 g kg⁻¹, was higher in PL than composts. The estimated PAN for PL and BSC remained relatively constant in 2003 and 2004, whereas it increased more than 60% for PLC from 2003 to 2004. The concentration of TP in PLC was 24 to 29% that of the BSC or PL. The PAN/TP ratio of PLC was similar to BSC in 2003 but was nearly twice as high in 2004. The PAN/TP ratio of PL was consistent both years and higher than either of the composted materials.

Net mineralization of organic P is expected to occur when the C/P ratio is less than 200:1 (Dalal, 1997). The C/P ratio of the organic residuals ranged from 15:1 to 94:1 and followed the order BSC>PL>PLC both years; thus, mineralization-immobilization transformations were not expected to influence P availability.

The CCE of BSC, due to the addition of Ca(OH)₂ during wastewater treatment, was 45% in 2003 and 34% in 2004. The high CCE and resulting increased pH was expected to influence P solubility in the organic residual and amended soil.

Phosphorus Solubility

Selected P solubility characteristics of the organic amendments applied in 2003 and 2004 are listed in Table 2. The EPA 3050B acid peroxide digestion method was developed to determine the “environmentally available” metal content of sediments, sludges, and soils (USEPA, 1986). This method has also been used to determine the concentrations of P and P-binding constituents (i.e., Fe, Al, and Ca) in organic residuals (Maguire et al., 2001; Penn and Sims, 2002). By design, the method does not dissolve metals bound to silicates because they are not considered environmentally available (USEPA, 1986). The concentrations of P in each of the residuals determined by EPA 3050B (Table 2) and EPA 3052 (Table 1), a total digestion procedure, were very similar. Therefore, EPA3050B may be a suitable assay for determining total P in organic residuals.

Phosphorus solubility in residual-amended soils is controlled by the concentrations of Fe, Al, and/or Ca in the applied residuals (Sharpley and Sisak, 1997; Maguire et al., 2000; Sharpley and Moyer, 2000; Penn and Sims, 2002). The 3050Ca concentration of BSC was higher in 2003 and 2004 (186 and 132 g kg⁻¹, respectively) than in either PLC or PL (Table 2). The 3050Ca concentration of PLC and PL was similar in 2003 (25.6 and 24.6 g kg⁻¹, respectively) and 2004 (18.5 and 25.3 g kg⁻¹, respectively). The 3050Fe content varied widely among the organic amendments ranging from approximately 1 to 30 g kg⁻¹. The concentrations of 3050Al also varied widely among the organic residuals, ranging from approximately 0.5 to 12 g kg⁻¹, following the same trend as 3050Fe (Table 2). Based on the relative concentrations

Table 1. Selected chemical properties of organic residuals applied in 2003 and 2004.

Residual	TKN [†]	NH ₄ -N	NO ₃ -N	PAN [‡]	C [§]	TP [¶]	PAN/TP	C/N	C/TP	CCE ^{††}
	g kg ⁻¹									%
2003										
PL	55.7	8.6	1.6 × 10 ⁻³	36.9	471	17.2	2.1	8.0	27	3.25
PLC	18.3	<1 × 10 ⁻¹	5.6 × 10 ⁻¹	1.89	381	4.30	0.44	21	89	7.09
BSC ^{‡‡}	20.1	2.4	1.64	5.81	221	14.7	0.40	11	15	44.8
2004										
PL	56.5	7.7	3.6 × 10 ⁻²	37.0	476	18.0	2.1	8.0	26	6.20
PLC	20.2	2.0 × 10 ⁻¹	8.9 × 10 ⁻¹	3.09	377	4.00	0.77	19	94	7.94
BSC	26.0	3.9	1.1 × 10 ⁻¹	6.22	257	16.5	0.38	10	16	34.3

[†] Total Kjeldahl nitrogen by EPA 351.3 (USEPA, 1979).

[‡] Plant-available nitrogen. Estimated by adding 100% of the measured (NO₃+NH₄)-N and the fraction of organic N estimated to be mineralizable during the first season. Mineralization coefficients used were 0.1 for composted residuals and 0.6 for poultry litter.

[§] Organic carbon by EPA 415.1 (USEPA, 1999).

[¶] Total phosphorus, by EPA 3052 microwave assisted digestion (USEPA, 1999).

^{††} Calcium carbonate equivalence by AOAC 955.01 (AOAC, 2000).

^{‡‡} PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

Table 2. Selected chemical characteristics of organic residuals applied in 2003 and 2004.

Residue	3050†				WS‡
	P	Ca	Fe	Al	P
	g kg ⁻¹				
2003					
PL	15.9	24.6	0.976	0.57	3.46
PLC	4.54	25.2	11.6	6.40	0.38
BSC§	15.2	186	29.9	12.2	0.006
LSD¶	0.67	8.21	1.10	0.50	0.21
2004					
PL	15.7	25.3	0.822	0.360	3.26
PLC	4.32	18.5	7.00	3.68	0.494
BSC	17.5	132	32.1	11.5	0.035
LSD	1.91	7.89	1.86	0.647	0.13

† Extractable P, Al, Fe, and Ca by the EPA 3050B acid peroxide method (USEPA, 1986).

‡ Water soluble P (1:10 ratio analyte/deionized water, 2 h reaction time, filtered through a 0.45-Millipore filter; Self-Davis and Moore, 2000).

§ PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

¶ LSD, least significant difference. Differences between means greater than LSD indicate significant difference at $p < 0.05$.

of P-binding constituents, we expected P solubility in the amended soil to differ markedly among treatments.

In recently amended soils or where residuals are surface applied, WSP of the organic residual has been shown to be a good indicator of the release of P to runoff (Sharpley and Moyer, 2000; Kleinman et al., 2002; Penn and Sims, 2002). Water soluble P of the organic amendments in this study ranged from 0.006 to 3.46 g kg⁻¹ and followed the trend PL>PLC>BSC (Table 2). The ratio WSP/3050P followed the same trend as WSP and was likely controlled by the relative concentration of P-binding constituents (Table 3). The WSP/3050P ratio of BSC was extremely low, only 0.04% in 2003 and 0.2% in 2004. Applied on an equivalent P basis, the relative risk of P loss immediately following application would be expected to be highest for PL, intermediate for PLC, and lowest for BSC. Leytem et al. (2004) reported similar WSP/3050P values for poultry litter (15 to 23%), dairy/

Table 3. Water soluble to EPA 3050 P and the molar ratios of EPA 3050 Ca/P and [Fe+Al]/P contained in residuals applied in 2003 and 2004.

Residue	WS‡:3050	3050†	
	P	Ca/P	[Fe+Al]/P
	%		
2003			
PL	21.8	1.2	0.08
PLC	8.28	4.29	3.03
BSC	0.04	9.43	2.00
LSD¶	1.59	0.13	0.10
2004			
PL	20.8	1.25	0.06
PLC	11.4	3.33	1.87
BSC	0.20	5.83	1.77
LSD	2.4	0.14	0.01

† Extractable P, Al, Fe, and Ca by the EPA 3050B acid peroxide method (USEPA, 1986).

‡ Water soluble P (1:10 ratio analyte/deionized water, 2 h reaction time, filtered through a 0.45-Millipore filter; Self-Davis and Moore, 2000).

§ PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

¶ LSD, least significant difference. Differences between means greater than LSD indicate significant difference at $p < 0.05$.

Table 4. Application rates of the organic amendment from 2000 to 2004.

Treatment	2000	2001	2002	2003†	2004
	Mg ha ⁻¹ (dw)				
PL‡	2.15	4.76	5.78	5.05	4.15
PLC	43.7	–	40.8	69.7	47.6
BSC	43.7	–	40.8	20.9	20.6

† Before 2003, both PLC and BSC treatments received poultry litter compost. In 2003, the treatments were modified to include biosolids compost.

‡ PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

beef manure compost (1.3 to 5.4%), and FeCl₂-treated biosolids (0.30%).

Amendment Application Rates

The application rates of the organic amendments from 2000 to 2004 are summarized in Table 4. Due to the wide range of estimated PAN among the organic amendments, the applied dry weight equivalent of the materials ranged from 4.15 to 69.7 Mg ha⁻¹ in 2003 and 2004. Whereas the application rates of PL and BSC treatments remained relatively constant each year, the rate of PLC treatments decreased by more than 30% from 2003 to 2004 due to an increase in estimated PAN in 2004.

The mass of TP applied to each treatment during the 5 yr of the study was 72.2 (CF), 355.3 (PL), 1059 (PLC), and 1217 (BSC) kg TP ha⁻¹ (Table 5). The PLC and BSC treatments received the same amount of P from 2000 to 2002 (before the treatments were modified) and similar amounts in 2003, but the PLC received about half as much P as the BSC in 2004 due to an increase in the PAN/TP ratio of PLC in 2004.

The quantity of C applied with the organic treatments ranged from 11 to 76 Mg ha⁻¹ between 2000 and 2002 (Table 5). The mass of C applied to the BSC treatment was 17 and 29% of that applied to PLC in 2003 and 2004 because the BSC had a higher concentration of PAN and a lower concentration of total C than PLC. Total C ap-

Table 5. Total phosphorus and organic carbon applied to agronomic treatments from 2000 to 2004.†

Treatment	2000	2001	2002	2003	2004	Sum
	kg ha ⁻¹					
P‡						
CF§	17.5	10.5	5.24	19.5	19.5	72.2
PL	30.1	71.4	92.5	86.6	74.7	355
PLC	253	–	317	299	190	1060
BSC	253	–	317	307	340	1220
	Mg ha ⁻¹					
C¶						
CF	–	–	–	–	–	–
PL	1.04	2.31	2.75	2.38	1.98	10.5
PLC	12.9	–	18.5	26.6	18.0	76.0
BSC	12.9	–	18.5	4.63	5.28	41.3

† Before 2003, both PLC and BSC treatments received poultry litter compost. In 2003, the treatments were modified to include biosolids compost.

‡ Phosphorus applied to organic residual treatments reported as determined by EPA 3052 (USEPA, 1999).

§ CTL, control; CF, commercial fertilizer; PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

¶ Total organic carbon applied to organic residual treatments reported as determined by EPA 415.1 (USEPA, 1999).

plied to the PL treatment over 5 yr was only about 14% of that applied to PLC.

Soil and Water Quality

Soil pH and Lime Application

Soil pH did not differ among treatments, with the exception of CF, before 2003 when compost treatments were modified. Soil pH was lower in the CF treatment than the CTL in all years. Soil pH ranged from 5.9 to 6.9 in 2003. The BSC treatment increased soil pH in 2003 due to the higher CCE of the BSC than the other amendments. To reduce confounding of soil chemical responses due to variable soil pH, $\text{Ca}(\text{OH})_2$ was applied in April 2004 to achieve a target pH of 7 (Sims, 1996). No $\text{Ca}(\text{OH})_2$ was applied to the BSC treatment. Application rates of $\text{Ca}(\text{OH})_2$ to the other treatments ranged from 1.35 to 2.31 Mg ha^{-1} and followed the order $\text{PLC} < \text{CTL} < \text{CF} < \text{PL}$.

Soil Test Phosphorus

In 2002, there were no differences in M1P, M3P, WSP, 3050P, P_{ox} , or DPS between PLC and BSC (Table 6). Soil test P and DPS of the PLC and BSC treatments were all significantly higher than the CTL before the application of the modified treatments in 2003.

The PL treatment increased M1P, M3P, and WSP in 2003 and 2004 compared to the CTL. Mehlich-1 P, M3P, and WSP remained significantly elevated by PLC and BSC in 2003 and 2004, but the PLC increased M1P, M3P, and WSP to a greater extent than BSC despite being applied at a similar P rate in 2003 and at a lower P rate in 2004.

The difference in P solubility between PLC and BSC is especially apparent for WSP in both 2003 and 2004.

Water soluble P from the PLC treatment was nearly twice as high as BSC and more than five times greater than the control in both 2003 and 2004. The WSP concentration of BSC actually decreased from 2002 to 2004. This indicates that some factor may be limiting P solubility in BSC that is absent in PLC. Both PLC and BSC had very similar molar ratios of $[\text{Fe} + \text{Al}]/\text{P}$ in both 2003 and 2004; however, the Ca/P ratio of BSC was far greater than PLC (Table 3). Siddique and Robinson (2003) reported an inverse relationship ($r^2 = 0.75$) between the increase in soluble P and the increase in exchangeable Ca in soils amended with poultry litter, poultry manure, and biosolids. Robinson and Sharpley (1996) attributed reduced availability of P from a poultry litter leachate-amended soil to its complexation with Ca and soluble organic compounds in the poultry litter. Calcium may play a key role in limiting P solubility in soils amended with organic residuals that have a low P/Ca ratio. This may be particularly true where soil pH is favorable for the precipitation of discrete Ca-P minerals (i.e., $\text{pH} > 6.5$), as was the case in the BSC treatment in 2003 and 2004.

Only the BSC and PLC treatments increased P_{ox} in 2003 and 2004. There were no differences in Fe_{ox} or Al_{ox} among treatments in 2003, but BSC increased both Fe_{ox} and Al_{ox} compared to the CTL in 2004. In 2004 the DPS ranged from 6.8 to 14.8% and followed the order $\text{CTL} = \text{CF} = \text{PL} < \text{BSC} = \text{PLC}$ in 2004. Beck et al. (2004) found that a DPS in excess of 20% in Virginia soils is associated with a marked decrease in P sorption capacity, and any increase in soil P beyond that point may result in an increased risk of P surface loss. It is likely that the DPS will exceed 20% with only a few more annual applications of BSC or PLC.

The concentrations of 3050P were higher in PLC and BSC than all other treatments before initiating the

Table 6. End of season Mehlich-1 P (M1P), Mehlich-3 P (M3P), water soluble P (WSP), EPA3050 P (3050P), acid ammonium oxalate P (P_{ox}), (Fe_{ox}), and (Al_{ox}) and the degree of P saturation (DPS_{ox}) from 2002 through 2004.

Treatment	pH	M1P	M3P	WSP	3050P	P_{ox}	Fe_{ox}	Al_{ox}	DPS_{ox}
		mg kg^{-1}							%
2002†									
CTL‡	6.30	12.3	19.0	1.28	1169	247.8	2569	2001	6.66
CF	5.90	16.5	27.1	1.57	1217	285.3	2428	2072	7.66
PL	6.28	20.0	33.4	2.04	1232	273.9	2277	1932	7.85
PLC	6.33	44.8	71.5	3.70	1374	353.6	2265	1909	10.3
BSC	6.29	44.0	66.8	3.35	1334	315.4	2110	1747	9.80
LSD§	0.29	12.3	18.4	0.985	79.71	57.75	349.8	262.7	1.19
2003									
CTL	6.20	12.0	19.4	0.890	1269	309.0	2361	2213	8.61
CF	5.85	16.3	28.1	1.09	1278	327.8	2312	2318	8.92
PL	6.20	23.0	38.8	1.93	1395	327.5	1971	2019	10.3
PLC	6.50	62.3	102	5.22	1487	514.0	2286	2039	15.3
BSC	6.86	46.3	83.8	2.33	1670	438.9	2214	1984	13.3
LSD	0.29	9.74	19.3	0.734	287.7	89.53	312.0	247.4	2.21
2004									
CTL	6.76	12.3	18.5	0.747	1065	242.9	1957	2280	6.79
CF	6.57	19.8	29.7	1.01	1119	256.3	1912	2039	7.68
PL	6.87	29.5	44.7	1.76	1233	317.7	1911	2151	9.33
PLC	6.91	85.3	120	5.89	1649	491.9	1820	2364	14.8
BSC	7.27	56.8	110	2.27	1299	660.1	2284	3282	14.5
LSD	0.21	15.2	24.6	1.24	188.0	151.7	824.2	459.9	2.45

† Samples taken for 2002 represent baseline values before treatment modification in 2003. Before 2003, both PLC and BSC treatments received poultry litter compost. In 2003, the treatments were modified to include biosolids compost.

‡ CTL, control; CF, commercial fertilizer; PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

§ LSD, least significant difference. Differences between means greater than LSD indicate significant difference at $p < 0.05$.

application of the BSC in 2003 (see Table 6, 2002) due to the higher TP applied with the high compost rates between 2000 and 2002. The annual application of all treatments except CF continued the temporal increase in 3050P. By 2004, 3050P concentration was much higher in the PLC treatment than in the rest of the treatments.

The concentration of WSP and M3P in the surface 0 to 5 cm of soil measured at the time of the rainfall simulation is given in Table 7. The concentrations of M3P and WSP (except in the PLC treatment) of the surface 0 to 5 cm of soil were approximately twice as high as those of the surface 0 to 15 cm, but all treatments followed the same trend. The CF, PL, PLC, and BSC treatments increased M3P and (except for CF) WSP in the surface 0- to 5-cm layer. The WSP concentration in the surface 0- to 5-cm layer of the PLC treatment was nearly five times greater than in the surface 15 cm.

Soil Carbon and Bulk Density

Total soil C was increased by both compost treatments and followed the order CTL≈CF = PL<BSC<PLC (Table 7). Total C in the PLC treatment was especially high, and at 40 g C kg⁻¹ was more than twice as high as CTL, CF, and PL treatments. In addition to more C being applied with the composts, soil C in compost-amended soil is more stable than in manure-amended soils due to microbial decomposition during the composting process (Robertson and Morgan, 1995; Hartz et al., 2000). Compost was considerably more effective at building total soil C than PL as assessed by calculating the increase in total soil C per unit of C applied with each of the organic residuals. The total soil C increased by 1.4 g kg⁻¹, or 2.6 Mg ha⁻¹ (assuming 2.2 million kg ha⁻¹ 15 cm⁻¹), with the PL application of 10.5 Mg C ha⁻¹ over 5 yr, which is approximately 25% of the C applied. By contrast, approximately 70% of the C applied persisted in the PLC treatment after 5 yr.

A significant portion of the increased persistence of soil C in the PLC treatment may also be due to increased biomass production from the cereal rye cover crop that was nearly twice that of the PL treatment (data not shown). Corn yield was similar among PLC, BSC, and CF treatments in both years (average 11.3 Mg ha⁻¹) and had nearly double the yield of the control (5.9 Mg ha⁻¹). This may have further accentuated the effects of the

Table 7. Water soluble P (WSP) and Mehlich-3 P (M3P) of the surface 5 cm and total soil C and N of the surface 15 cm at the time of rainfall simulation, September 2004.

Treatment	M3P	WSP	C		N
	mg kg ⁻¹		g kg ⁻¹		
CTL†	23.1	1.15	15.3	0.925	
CF	69.2	2.17	15.5	0.973	
PL	77.1	4.12	16.7	1.16	
PLC	247	28.1	40.0	2.73	
BSC	218	5.90	24.0	1.70	
LSD‡	36.2	2.26	3.20	0.265	

† CTL, control; CF, commercial fertilizer; PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

‡ LSD, least significant difference. Differences between means greater than LSD indicate significant difference at $p < 0.05$.

treatments on soil C; however, the impact was minimal since there is very little difference in total C between the CTL and CF treatments.

Both agronomic compost treatments reduced bulk density, but the bulk density in the PLC treatment (0.97 Mg m⁻³) was significantly lower than that in the BSC (1.22 Mg m⁻³). This appeared to be due to the greater C application rate of PLC in both 2003 and 2004, as bulk density was highly correlated with total soil carbon ($r^2 = 0.84$; Fig. 1). Such a reduction in bulk density with compost probably results from the dilution of soil mineral matter with less dense organic matter (Khaleel et al., 1981).

The striking increase in organic matter and decrease in bulk density have some important implications to soil and water quality. Increased organic matter and decreased bulk density in compost-amended soils have been associated with increased porosity, water-holding capacity, and plant-available water (Tester, 1990; Giusquiani et al., 1995) as well as decreased runoff and erosion (Khaleel et al., 1981; Aggelides and Londra, 2000; Evanylo and Sherony, 2002; Foley and Cooperband, 2002).

Rainfall Simulation

Runoff and Infiltration. The only treatment that increased the time from the commencement of rainfall to the initiation of runoff relative to CTL was PLC (Table 8). Likewise, infiltration was significantly greater and runoff significantly less from PLC than any other treatment (Table 8). The PL and BSC treatments also increased infiltration and decreased runoff compared to the CTL. Increased infiltration into and decreased runoff from the soils amended with organic residuals was likely due to the buffering of the raindrop impact, maintenance of aggregate stability, prevention of pore clogging, and increased water absorption and holding capacity by the added organic matter (Khaleel et al., 1981; Aggelides and Londra, 2000; Evanylo and Sherony, 2002; Foley and Cooperband, 2002). This is illustrated by the negative relationship between runoff and total soil C content ($r^2 = 0.60$, $p < 0.0001$; Fig. 2).

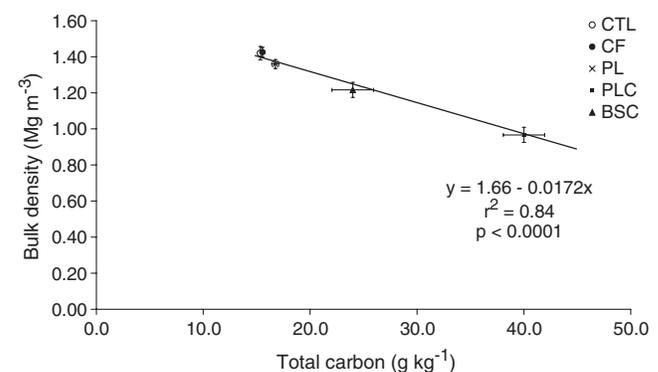


Fig. 1. Relationship between bulk density and total carbon in samples collected September 2004. Values are the average of four replications \pm SE. CTL, control; CF, commercial fertilizer; PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

Table 8. Infiltration, runoff, and time to initiation of runoff during rainfall simulation in September 2004.

Treatment	mm		Time to runoff min
	Infiltration	Runoff	
CTL†	23	25	8.5
CF	27	20	8.0
PL	37	17	14
PLC	86	6.7	45
BSC	41	14	15
LSD‡	35	6.9	25

† CTL, control; CF, commercial fertilizer; PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

‡ LSD, least significant difference. Differences between means greater than LSD indicate significant difference at $p < 0.05$.

Phosphorus and Sediment Concentrations. The concentration and mass loss of P in runoff is summarized in Table 9. The concentration of TP in runoff ranged from 1.98 to 3.88 mg L⁻¹ and was increased above the CTL only by BSC. The concentration of PP in runoff (1.05 to 2.63 mg L⁻¹) comprised 40 to 73% of the TP concentration. The majority of the P in runoff from the CTL, CF, and BSC treatments was in the PP form, whereas that from the PLC treatment was primarily TDP. The concentration of TDP in runoff from both agronomic compost treatments was significantly higher than other treatments and was significantly greater from PLC than from BSC. The decrease in the percent of PP in runoff from PLC is likely due to both reduced erosion and elevated soluble P (i.e., WSP). Dissolved reactive P is the P fraction in runoff that poses the greatest environmental risk, because its largely orthophosphate composition is immediately algal-available (Pote and Daniel, 2000). The concentration of DRP in runoff followed the same treatment trend as TDP. Only the BSC and PLC treatments increased the concentration of DRP in runoff, which was nearly two- and threefold higher in the BSC and PLC, respectively, than in the CTL.

Phosphorus and Sediment Mass Losses. The concentration of P in runoff may serve as an index of environmental risk; however, measurement of the mass loss of P is a more direct indication of environmental impact. Organic amendments can significantly

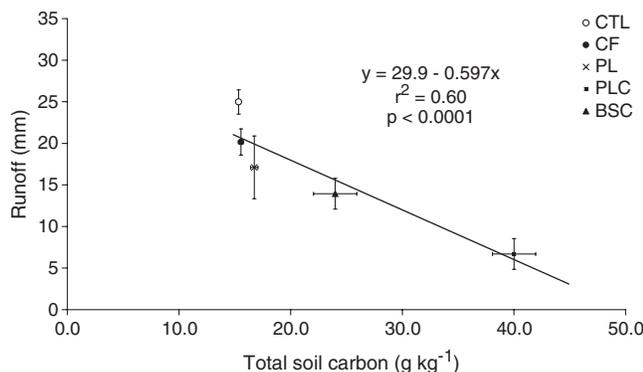


Fig. 2. Relationship between runoff and total soil carbon content. Values are the average of four replications \pm SE. CTL, control; CF, commercial fertilizer; PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

affect infiltration and thus confound the relationship between concentration and mass loss of P in runoff (Pote et al., 1996; Andraski and Bundy, 2003; McDowell and Sharpley, 2003). The mass loss of TP (ranging from 218 to 647 g ha⁻¹) was reduced by PL and PLC treatments (Table 9). Differences in mass loss of TDP, which ranged from 116 to 178 g ha⁻¹, were not observed among treatments. The mass loss of PP was lower from both PL and PLC treatments.

The concentration of DRP in runoff was related to M3P and WSP in the surface 5 cm of soil ($r^2 = 0.68$ and 0.72 , $p < 0.0001$; Fig. 3). The concentration of DRP in runoff was also related to WSP ($p < 0.001$), M3P ($p < 0.001$), and DPS_{ox} ($p < 0.01$) of the surface 0- to 15-cm layer of soil; however, only 51, 50, and 40% of the variability could be explained by changes in WSP, M3P, and DPS_{ox} values, respectively.

Soil P extraction methods and the mass loss of DRP were not related due to large differences in infiltration and runoff among treatments. Our results support the validity of using WSP and M3P of the surface 5-cm soil layer to predict DRP concentrations in surface runoff and confirm their inadequacy in predicting the mass loss of P when treatments affect infiltration and runoff.

Our results are consistent with those of McDowell and Sharpley (2003), who demonstrated the critical role of soil C in controlling the mass loss of P in runoff from a Hagerstown silt loam (Typic Hapludalfs) that had received poultry manure, dairy manure, or triple superphosphate at five rates from 0 to 200 kg ha⁻¹ for 5 yr. The authors found that sediment loss was inversely related to the degree of aggregation ($r = 0.51$) and hydrolyzable carbohydrate ($r = 0.62$). The loss of total P in runoff from soil treated with up to 50 kg P ha⁻¹ as manure was not significantly greater than untreated soil, due to increased aggregation and decreased soil slaking attributed to added C in manure. Andraski and Bundy (2003) and Pote et al. (1996) suggested that the development of an accurate method for predicting runoff volume could be combined with soil test P for the prediction of the mass loss of P. It is apparent that such a model will depend heavily on soil C concentrations, particularly in soils amended with organic residuals.

The greater loss of P from the BSC than the PLC treatment demonstrates the importance of transport factors, such as runoff, in controlling P loss. The concentration of P-binding constituents also influences the loss of P in runoff. This is seen by comparing the concentrations of P_{ox} and 3050P with runoff P among treatments. The concentration of P_{ox} in BSC-amended soil was more than twice as high as the CF or PL treatments; however, the concentration and mass loss of DRP among the three treatments were similar.

Mass loss of TOC was not different among treatments. The mass loss of TSS was lower in all treatments than the CTL and was drastically reduced by PLC. It is interesting that the CF treatment reduced erosion by half of that from the CTL, despite providing no direct addition of organic matter and no increase in total soil carbon. This may be a result of improved aggregate stability

Table 9. Mean P fraction, organic carbon and sediment concentration, and mass loss in runoff during rainfall simulation in September 2004.†

Treatment	DRP†	DURP	TDP	PP	TP	TOC	TSS
	mg L^{-1}						
CTL‡	0.185	0.395	0.580	2.00	2.58	1.23	1130
CF	0.228	0.553	0.780	1.65	2.43	1.52	716
PL	0.295	0.633	0.928	1.05	1.98	1.95	836
PLC	0.540	1.10	1.635	1.29	2.93	2.40	516
BSC	0.373	0.875	1.248	2.63	3.88	1.74	782
LSD§	0.177	0.290	0.400	1.00	1.09	0.826	403
	g ha^{-1}						
CTL	46.6	98.2	145	502	647	309	283
CF	45.6	111	156	326	482	314	140
PL	51.3	103	154	192	346	351	151
PLC	38.1	77.8	116	102	218	188	35.0
BSC	53.8	124	178	350	528	240	111
LSD	25.3	55.6	80.0	192	210	169	85.9

† DRP, dissolved reactive phosphorus; DURP, dissolved unreactive phosphorus; TDP, total dissolved phosphorus; PP, particulate phosphorus; TP, total phosphorus; TOC, total organic carbon; TSS, total suspended solids.

‡ CTL, control; CF, commercial fertilizer; PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

§ LSD, least significant difference. Differences between means great than LSD indicate significant difference at $p < 0.05$.

associated with the increased ionic strength of fertilized soils (Haynes and Naidu, 1998).

CONCLUSIONS

The reduced mass loss of both TDP and PP from the PLC treatment illustrates the importance of improved soil tilth in limiting P loss in runoff. Although the PLC treatment increased soil test P concentrations to near environmental thresholds, the risk of P loss was reduced threefold relative to the CTL and twofold relative to the CF, PL, and BSC treatment. Curiously, the BSC treatment resulted in considerably higher P runoff loss than the PLC despite causing lower soil WSP than the PLC. Our results demonstrate that the soil factors that control infiltration and runoff (e.g., organic matter, bulk density, water-holding capacity, aggregate stability) may be as important as the chemical factors that control P solubility (e.g., concentration of P-binding Ca, Fe, or Al).

Four consecutive N-based compost applications did not increase the risk of runoff losses of P, and in the case of PLC actually decreased it. What is not clear is how many more years of N-based applications it will take before water quality is threatened. For the BSC treat-

ment, we expect that runoff P will be increased after one or two more applications. Our results suggest that for the PLC treatment, it could take many more applications before the concentration of P in soil solution is high enough that the reduced runoff is no longer sufficient to prevent deleterious runoff P losses. Land application of composted organic residuals is a viable alternative management option for biosolids and manure for the reduction of P losses in surface runoff.

An important P loss pathway that our research did not address is leaching. It is possible that higher concentrations of WSP coupled with increased infiltration in the compost-treated soils may lead to P movement to greater depths, potentially saturating the P sorption capacity at lower depths and threatening ground water quality. This may be especially true in coarse-textured soils with low P-sorption capacity and with a high groundwater table and/or high lateral shallow subsurface flow. In deep, fine-textured, high P-fixing Piedmont soils similar to the Fauquier silty clay loam, leaching losses are likely minimal; however, future research will need to be conducted to confirm this.

ACKNOWLEDGMENTS

The authors would like to thank David Starner, Mike Brosius, Chandra Bowden, Beshir Sukkariyah, and Kathryn Haering for their technical assistance in the field and in the lab. Partial funding for this research was provided by the Virginia Corn Board and The United States Department of Agriculture Sustainable Agriculture Research and Education program.

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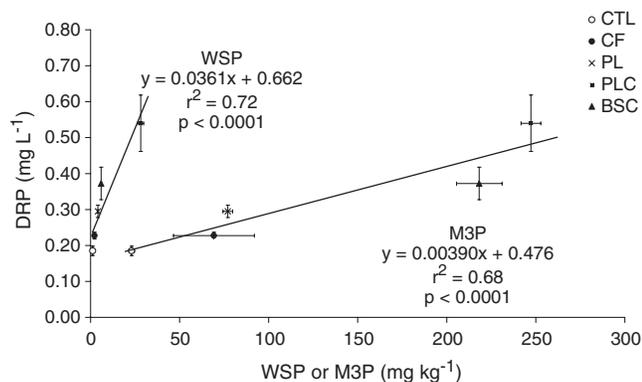


Fig. 3. Relationship between water soluble P (WSP) or Mehlich-3 P (M3P) in the surface 5-cm layer of soil and dissolved reactive P (DRP) in runoff. Values are the average of four replications \pm SE. CTL, control; CF, commercial fertilizer; PL, poultry litter; PLC, poultry litter-yard waste compost; BSC, biosolids compost.

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