Effect of Mineral and Manure Phosphorus Sources on Runoff Phosphorus

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ABSTRACT

Concern over nonpoint-source phosphorus (P) losses from agricultural lands to surface waters has resulted in scrutiny of factors affecting P loss potential. A rainfall simulation study was conducted to quantify the effects of alternative P sources (dairy manure, poultry manure, swine slurry, and diammonium phosphate), application methods, and initial soil P concentrations on runoff P losses from three acidic soils (Buchanan–Hartleton, Hagerstown, and Lewbeach). Low P (12 to 26 mg kg^{-1} Mehlich-3 P) and high P (396 to 415 mg kg^{-1} Mehlich-3 P) members of each soil were amended with 100 kg total P ha^{-1} from each of the four P sources either by surface application or mixing, and subjected to simulated rainfall (70 mm h^{-1} to produce 30 min runoff). Phosphorus losses from fertilizer and manure applied to the soil surface differed significantly by source, with dissolved reactive phosphorus (DRP) accounting for 64% of total phosphorus (TP) (versus 9% for the unamended soils). For manure amended soils, these losses were linearly related to water-soluble P concentration of manure (r^2 = 0.86 for DRP, r^2 = 0.78 for TP). Mixing the P sources into the soil significantly decreased P losses relative to surface P application, such that DRP losses from amended, mixed soils were not significantly different from the unamended soil. Results of this study can be applied to site assessment indices to quantify the potential for P loss from recently manured soils.

The widespread development of site assessment indices to rank the relative potential of nonpoint-source P loss from agricultural lands has resulted in a detailed examination of "source" and "transport" factors affecting P loss (Lemunyon and Gilbert, 1993; Sharpley et al., 1996; Gburek and Sharpley, 1998; Frossard et al., 2000). Major source factors include soil P concentration, rate, method and timing of P additions, and inherent properties of manure and mineral P amendments (Kleinman, 2000). At present, several states have proposed (Delaware, Florida, Pennsylvania) or implemented (Arkansas, Maryland, Oklahoma) P indices that allow for manure and mineral P sources to be weighted differently (Weld et al., 2000). Ideally, the basis for distinguishing between P sources should be their potential to release P to runoff.

A variety of factors affect the potential for P loss from soils amended with manure or mineral fertilizer. Phosphorus chemical fractionation, particularly with regard to solubility in water, probably controls DRP concentrations in runoff (McDowell and Sharpley, 2001). For instance, Pote et al. (1999) found that DRP concentrations in surface runoff were related ($r > 0.9$) to water-extractable soil P in three acidic soils. Because manure and mineral fertilizer P application to soils may result in dramatic, temporary increases in water-extractable P, forms of P added to soil play an important role in P availability to runoff. In fact, Moore et al. (2000a) reported significant differences in DRP losses from pastures amended with either alum-treated or untreated poultry litter. They observed concomitant decreases in the water-soluble P fraction of poultry litter treated with alum and runoff DRP losses from the pasture receiving that litter.

In addition to affecting the availability of P to runoff water, manure and mineral fertilizer P sources may directly affect soil physical properties that control runoff and erosion. Over the short term, surface application of manure, particularly at high loading rates, may improve soil surface protection from raindrop impact and aggregate dispersion (Barthès et al., 1999; McDowell and Sharpley, 2003). Over the long term, addition of manure may increase soil organic matter levels, which in turn affects porosity, aggregate stability, and infiltration, factors that affect runoff and erosion potential (Rousseva, 1989; Oades and Waters, 1991; Gilley and Risse, 2000).

The method by which a P source is applied also influences P loss in runoff (Romkens et al., 1973; Mueller et al., 1984; Zhao et al., 2001). Surface application of manure and mineral fertilizer concentrates P at the soil surface where it is vulnerable to removal by runoff (Sharpley et al., 1984; Eghball and Gilley, 1999). For instance, Sharpley (1985) reported an effective depth of interaction (EDI) between surface runoff and soil P of 1.3 to 37.4 mm, depending upon rainfall intensity and slope gradient. As a result, surface placement may greatly increase DRP losses. Injection, knifing, and immediate incorporation by cultivation remove manure and fertilizer from the EDI zone, but, in the case of cultivation, may also result in increased vulnerability to particulate P losses due to increased erosion potential (Romkens et al., 1973; Andraski et al., 1985).

Timing of manure and mineral fertilizer application relative to runoff event plays a key role in the magnitude of observed P losses (Sharpley, 1997; Westerman and Overcash, 1980). Immediately following application of a P source, the potential for P loss peaks and then declines over time, as applied P increasingly interacts with the soil and is converted from soluble to increasingly recalcitrant forms (Edwards and Daniel, 1993). Sharpley and Syers (1979) reported declining DRP (from >0.25 mg L^{-1} to <0.1 mg L^{-1}) and TP concentrations (from >0.7 mg L^{-1} to <0.1 mg L^{-1}) in tile drainage over one month following temporary, intensive grazing of paddocks by dairy cattle. Similarly, Gascho et al. (1998) observed exponential declines in DRP concentrations in runoff (from >5 mg L^{-1} to <1 mg L^{-1}) over

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Abbreviations: DAP, diammonium phosphate; DRP, dissolved reactive phosphorus; SS, suspended solids; TP, total phosphorus.

Table 1. Properties of Buchanan–Hartleton, Hagerstown, and Lewbeach soils used in study.

Soil	Mehlich-3 P	CEC†	pH (1:1 water)	P sorption saturation	Particle size distribution		
					Sand	Silt	Clay
	mg kg^{-1}	cmol kg^{-1}		%	%		
Hartleton–Buchanan, low P	26	10.3	5.4	7	41	32	27
Hartleton–Buchanan, high P	410	14.2	5.9	31	36	37	27
Hagerstown, low P	12	16.3	7.5	7	14	39	47
Hagerstown, high P	415	17.5	6.8	29	20	45	35
Lewbeach, low P	13	17.2	4.6	4	41	39	20
Lewbeach, high P	396	16.8	6.6	23	45	35	20

† Cation exchange capacity.

roughly one month after mineral fertilizer application. However, little information is available on the relative effects of the type, method, and timing of added P on P loss potential.

This study quantifies the differential effects of alternative P sources, application methods, and initial soil P on runoff P losses from three acidic soils (Hagerstown, Buchanan–Hartleton, and Lewbeach). Specifically, four P sources (dairy manure, poultry manure, swine slurry, and diammonium phosphate) were applied by two methods (surface application and mixing) at the same rate of TP addition (100 kg TP ha^{-1}) to low P (Mehlich-3 P of 12 to 26 mg kg^{-1}) and high P (Mehlich-3 P of 396 to 415 mg kg^{-1}) members of the three soils.

MATERIALS AND METHODS

Soils and Phosphorus Sources

Three acidic soils, Hagerstown (fine, mixed, semiactive, mesic Typic Hapludalf), Lewbeach (coarse-loamy, mixed, semiactive, frigid Typic Fragiudept) and a Buchanan (fine-loamy, mixed, semiactive, mesic Aquic Fragiudult)–Hartleton (loamy-skeletal, mixed, active, mesic Typic Hapludult) association, were selected for analysis (Table 1). Surface samples (0–10 cm depth) of low- and high-P soil were collected from agricultural fields, sieved (2 mm) under dry field conditions, and stored at 24°C prior to analysis.

Soils were analyzed for Mehlich-3 P by shaking 2.5 g of soil in 25 mL of Mehlich-3 solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.013 M HNO_3 + 0.001 M EDTA) for 5 min. The supernatant was filtered (0.45 μm), and P in the neutralized filtrate determined by the method of Murphy and Riley (1962). Soil cation exchange capacity (CEC) was determined by summation of Mehlich 3–extractable cations. Soil pH was determined by mixing 5 g air-dry soil with 5 mL distilled water.

Soil P sorption saturation was determined by shaking 0.25 g of soil in 10 mL of acid oxalate solution [0.1 M $(NH_4)_2C_2O_4 \cdot H_2O$ + 0.1 M $H_2C_2O_4 \cdot 2H_2O$] for 4 h in the dark, centrifuging (510 × g for 20 min), and then filtering (0.45 μm) the extract (Ross and Wang, 1993). Extractable P, Fe, and Al concentrations were determined by ICP, and molar concentrations of each element used to calculate soil P sorption saturation as follows (Beauchemin and Simard, 2000):

$$\text{P sorption saturation} = \text{P}/(\text{Fe} + \text{Al})$$

Four P sources were selected for analysis: dairy manure, poultry manure, swine slurry, and diammonium phosphate (DAP) (18–46–0 N–P–K). Total P and N were measured on all manures by modified semimicro-Kjeldahl procedure (Bremner, 1996). Water-soluble P was determined for all P sources (mineral and manure) by the method of Sharpley and Moyer (2000). Following dry matter determination of manures, approximately 1 g (dry weight) of field moist manure was shaken for 1 h in 200 mL distilled water. The supernatant was then filtered (Whatman[1] [Maidstone, UK] #1) and P determined in the filtrate by the colorimetric method of Murphy and Riley (1962). Manure and fertilizer pH were measured after mixing with distilled water (1 g to 100 mL). Dry matter content of the manures was obtained by gravimetric analysis (manures dried at 105°C for 48 h).

Runoff Experiment

A runoff experiment was designed to test the effects of P source, soil properties, and P application method on runoff P losses with the National Phosphorus Research Project indoor runoff box protocol (National Phosphorus Research Project, 2001). The protocol employs stainless steel runoff boxes, 1 m long, 20 cm wide and 5 cm deep with back walls 2.5 cm higher than the soil surface, and 5-mm drainage holes in the base (Fig. 1). Cheese cloth is placed on the bottom of the box, followed by sufficient soil to achieve a bulk density of 1.3 to 1.5 g cm^{-3}. Runoff is generated by applying artificial rainfall on inclined (3%) soil runoff boxes with a TeeJet 1/2 HH SS 50 WSQ nozzle (Spraying Systems Co., Wheaton, IL) placed approximately 305 cm above the soil surface. Rainfall is delivered at approximately 70 mm h^{-1}, and has a coefficient of uniformity > 0.83 within the 2- × 2-m area directly below the nozzle (coefficient of uniformity = standard deviation × mean^{-1} of rainfall intensity as determined on a 20-cm grid spacing). Runoff is collected via a gutter, equipped with a canopy to exclude direct input of rainfall and inserted at the lowest edge of the runoff box (Fig. 1).

After packing soils into runoff boxes, P sources were applied at a TP rate of 100 kg ha^{-1} by either broadcasting them onto the soil surface or mixing them with the soil. This rate of application approximates the recommended N-based manure application rate of 300 kg N ha^{-1} for silage corn (Beegle, 1999), given that that average total N to TP ratio of the three manures was 3.4 (Table 2). Each treatment was conducted in duplicate. To ensure that initial soil moisture was consistent between all treatments, soils were irrigated to approximately field capacity (θ = approximately 0.30), factoring in contributions of water from the manures themselves. Within 72 h of P application to the packed soils, artificial rainfall was applied to the soils and the initial 30 min of runoff collected.

A runoff sample was collected from each box, and after thorough mixing and agitation, a subsample was immediately filtered (0.45 μm). Filtered and unfiltered samples were stored at 4°C, and filtered samples were analyzed within 24 h of collection whereas unfiltered samples were analyzed within 7 d of the rainfall-runoff event.

[1] Mention of trade names does not imply endorsement by the USDA.

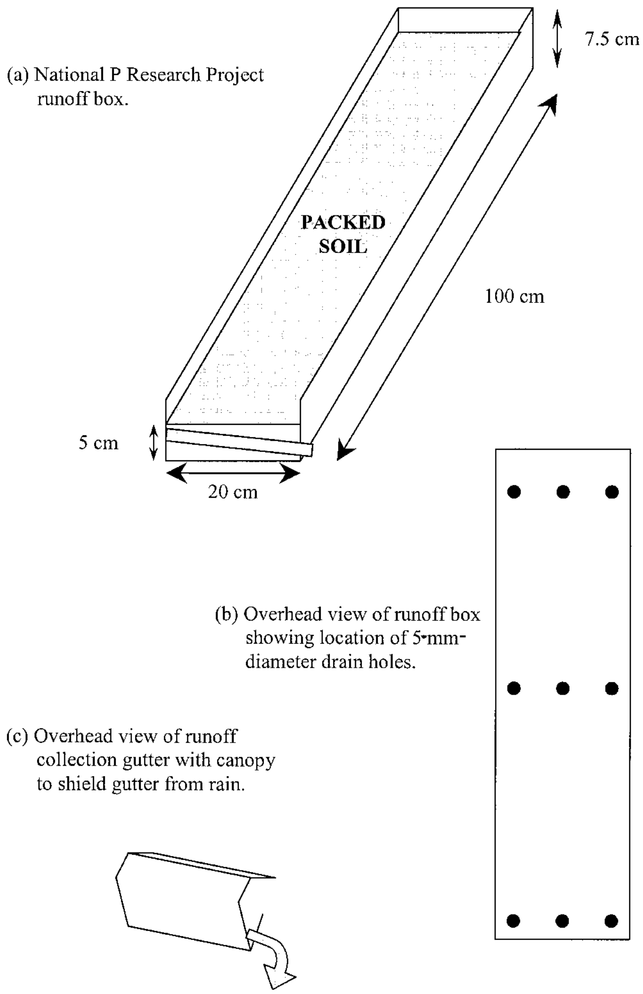

Fig. 1. Schematic diagram of runoff box used in this study including (*a*) overall dimensions, (*b*) drain holes in base of box, and (*c*) runoff collection gutter.

The concentration of DRP in surface runoff was determined on filtered samples and TP on unfiltered runoff water by the modified semimicro-Kjeldahl procedure (Bremner, 1996). Phosphorus in all filtrates and neutralized digests was determined by the colorimetric method of Murphy and Riley (1962). Suspended solids (SS) were determined by gravimetric analysis, after evaporating 200 mL of runoff water at 80°C.

Statistical Analysis

Differences in runoff quality were analyzed by analysis of variance (ANOVA). Data were transformed as necessary to conform with the assumptions of normality and equality of variance. Concentration data were square root–transformed and load data were cube root–transformed; runoff volume data were analyzed on the original scale. Since the interaction between P source and initial soil P was usually significant, sets of single-degree-of-freedom contrasts were used to test various hypotheses. To address the problem of multiple comparisons, p values were adjusted with the stepdown Sidak approach (SAS Institute, 1999). Relations between water-soluble P of the sources, SS, and runoff P were assessed by Pearson's correlation analysis, and modeled by least squares regression with qualitative variables for soil and initial soil P. In this type of model, the interaction terms between the quantitative and qualitative variables provide tests of homogeneity of the regression coefficients (Neter et al., 1996). For all analyses, a threshold of $p < 0.05$ was used to assess statistical significance.

RESULTS AND DISCUSSION

Soil and Phosphorus Source Properties

The physical and chemical properties of the three selected soils are presented in Table 1. The Mehlich-3 P concentrations ranged from 12 to 26 mg kg^{-1} for soils considered "low P," and from 396 to 415 mg kg^{-1} for "high P" soils. For the P sources, the TP and water-soluble P concentrations of DAP were 6 to 83 times greater than in the manure sources (Table 2). Roughly 80% of TP in the DAP fertilizer was water soluble, whereas 33, 26, and 27% of the TP in dairy manure, poultry manure, and swine slurry, respectively, were water soluble. Notably, although all P sources were alkaline, the pH of poultry manure was greater than the other sources (Table 2).

Runoff Phosphorus Losses following Surface Application

The concentrations of DRP and TP in runoff from soils receiving surface application of DAP, poultry manure, and swine slurry were significantly greater than in runoff from the unamended (control) soils (Fig. 2 and 3). Runoff DRP and TP concentrations from the dairy manure–amended soils were greater than, but not always significantly different from, runoff P concentrations from unamended soils (Fig. 2 and 3). Runoff volumes did vary somewhat between treatments for the Buchanan–Hartleton soil. For instance, "high P" runoff volumes were significantly lower than "low P" runoff volumes ($p < 0.01$). Volumes from dairy manure– and swine manure–amended soils were significantly greater than from DAP and unamended soils ($p < 0.05$), but not significantly different from poultry manure–amended soils. Despite these few differences in runoff volume, comparisons of runoff DRP and TP loads (mg) from unamended and amended soils result in the same conclusions as those drawn from concentration (mg L^{-1}) data (Table 3).

These results confirm the role of recently applied P

Table 2. Properties of manures and mineral fertilizer used in study.

P source	Dry matter	Total N	Total P	Water-soluble P	pH
	g kg^{-1}	g kg^{-1} (dry wt. basis)			
Diammonium phosphate	**1000**	**180**	**200**	**160**	**7.2**
Dairy manure	**157**	**30**	**6**	**2**	**8.0**
Poultry manure	**527**	**35**	**23**	**6**	**8.9**
Swine slurry	**16**	**117**	**33**	**9**	**7.3**

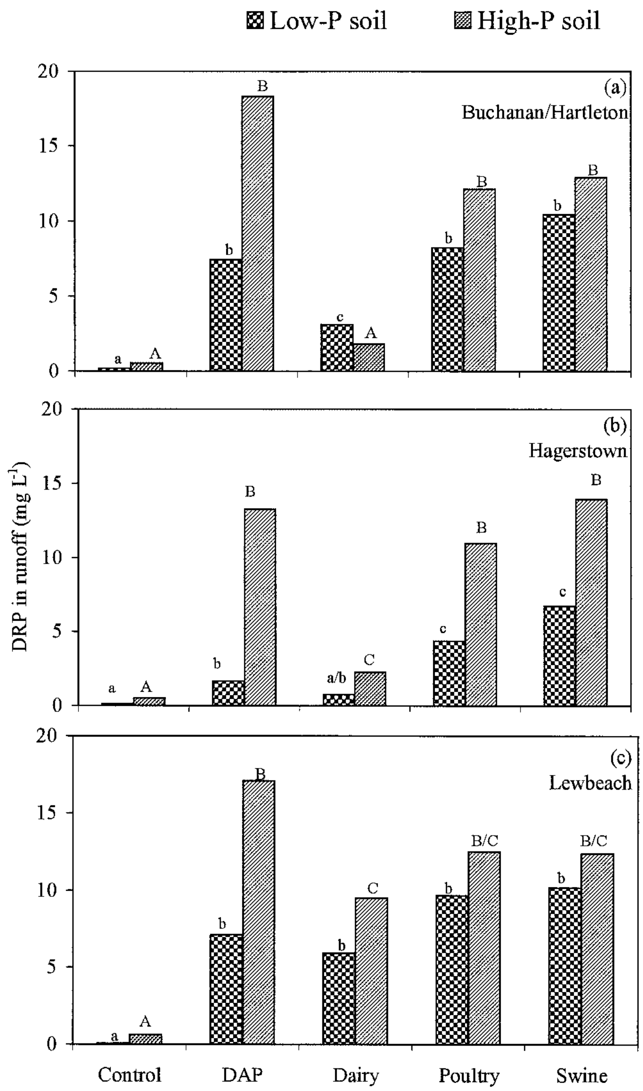

Fig. 2. Mean runoff DRP concentrations following surface application of P sources to (*a*) Buchanan–Hartleton, (*b*) Hagerstown, and (*c*) Lewbeach soils. Letters above bars columns identify groupings of means that are not significant at $p = 0.05$, with lowercase denoting low-P soils and uppercase denoting high-P soils. Hypothesis tests were conducted on square root–transformed data.

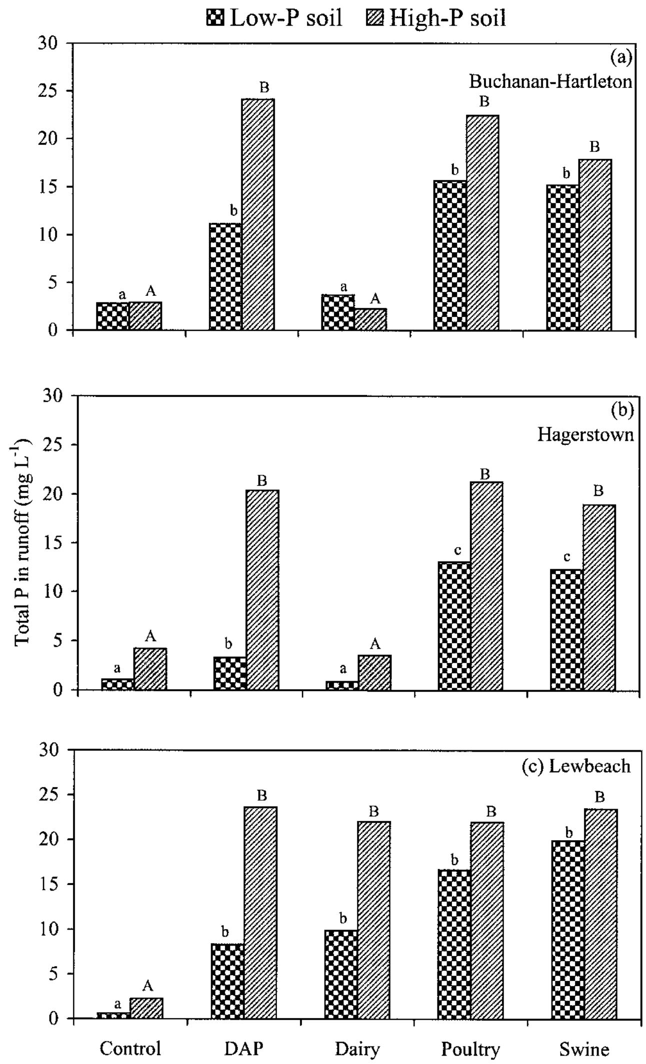

Fig. 3. Mean runoff total phosphorus (TP) concentrations following surface application of P sources to (*a*) Buchanan–Hartleton, (*b*) Hagerstown, and (*c*) Lewbeach soils. Letters above bars columns identify groupings of means that are not significant at $p = 0.05$, with lowercase denoting low-P soils and uppercase denoting high-P soils. Hypothesis tests were conducted on square root–transformed data.

as a key source of P in runoff. Indeed, while Mehlich-3 P and soil P sorption saturation were well correlated with runoff DRP concentrations from the unamended soils ($r = 0.76$ for Mehlich-3 P; $r = 0.77$ for P sorption saturation), they were poorly correlated with runoff DRP concentrations from surface-amended soils ($r = 0.47$ for Mehlich-3 P; $r = 0.37$ for P sorption saturation). The lower correlation of Mehlich-3 P and soil P sorption saturation with runoff DRP concentrations from amended soils suggests that soil P contributes little to runoff P losses following recent surface application. The greater concentrations of P in runoff from amended soils may be attributed to greater availability of soluble P at the soil surface, as DRP in runoff water accounted for 64% of TP from the amended soils, whereas DRP in runoff water accounted for only 9% of TP from the unamended soils.

Role of Surface-Applied Phosphorus Source

In comparing runoff P concentrations from amended soils, surface application of dairy manure consistently resulted in the lowest runoff DRP (0.7 to 9.5 mg L^{-1}) and TP concentrations (0.9 to 22.0 mg L^{-1}), although differences between dairy and other amendments were not always statistically significant (Fig. 2 and 3). As mentioned above, runoff DRP and TP losses from many of the dairy manure–amended soils were not significantly different than those from unamended soils. These similarities are somewhat misleading, as they imply that dairy manure did not contribute significantly to runoff P content beyond what was already contributed by the soil. In fact, substantial differences in the form of runoff P between the control and dairy manure–amended soils indicate that P from the dairy manure, not soil P, was the primary source of runoff P following dairy manure

Table 3. Runoff loads of suspended solids (SS), dissolved reactive phosphorus (DRP), and total phosphorus (TP) following application of P sources and associated runoff volumes.

Soil	Control (no P application)				Diammonium phosphate				Dairy manure				Poultry manure				Swine slurry			
	Runoff volume	SS	DRP	TP	Runoff volume	SS	DRP	TP	Runoff volume	SS	DRP	TP	Runoff volume	SS	DRP	TP	Runoff volume	SS	DRP	TP
	mL	——— mg ———			mL	——— mg ———			mL	——— mg ———			mL	——— mg ———			mL	——— mg ———		
	Surface application of P source																			
Buchanan–Hartleton low-P soil	3 050	2 734	0.3	6.0	3 960	4 964	29.3	44.0	1 025	379	3.2	3.8	3 595	4 210	29.6	56.2	2 825	1 471	29.6	43.1
Buchanan–Hartleton high-P soil	5 404	9 869	2.0	19.0	4 710	4 827	86.1	113.2	1 778	858	3.4	4.1	5 773	10 591	70.7	132.7	2 515	1 225	32.7	45.3
Hagerstown low-P soil	1 809	2 542	0.2	2.4	2 015	3 366	3.2	6.4	608	275	0.6	0.6	1 203	1 693	6.1	16.0	2 493	1 281	9.3	26.3
Hagerstown high-P soil	5 481	7 502	1.8	24.6	5 483	6 430	72.6	111.8	3 780	751	8.5	13.4	5 185	5 904	56.9	110.3	5 660	2 901	78.8	107.3
Lewbeach low-P soil	3 645	2 481	0.1	3.7	4 308	2 206	30.7	36.0	4 425	3 938	26.4	44.4	4 500	4 379	43.2	74.3	5 915	7 554	60.2	117.7
Lewbeach high-P soil	5 706	1 129	2.2	26.7	4 925	6 443	85.1	117.8	4 750	10 383	48.0	113.2	6 465	9 632	80.9	141.8	5 970	7 248	73.9	139.9
	Mixing of P source and soil																			
Buchanan–Hartleton low-P soil	3 050	2 734	0.3	6.0	4 030	3 873	1.5	6.9	6 725	14 227	1.4	28.2	4 350	4 181	4.9	16.6	6 685	11 920	1.5	22.2
Buchanan–Hartleton high-P soil	5 404	9 869	2.0	19.0	6 080	11 287	8.4	30.2	6 480	22 748	3.5	53.3	6 600	11 518	3.9	28.0	6 260	18 241	2.5	39.3
Hagerstown low-P soil	1 809	2 542	0.2	2.4	1 620	1 216	0.4	2.6	4 375	8 242	1.8	20.4	3 470	3 591	1.1	8.1	4 140	6 621	0.9	8.9
Hagerstown high-P soil	5 481	7 502	1.8	24.6	6 925	11 460	2.9	33.3	5 800	17 135	2.9	52.1	6 020	15 278	2.4	39.4	6 270	17 500	2.1	43.2
Lewbeach low-P soil	3 645	2 481	0.1	3.7	4 955	4 405	0.4	14.3	5 585	12 551	0.7	38.7	5 040	6 698	0.5	20.0	6 690	15 121	0.7	32.0
Lewbeach high-P soil	5 706	11 299	2.2	26.7	5 020	7 582	8.0	25.0	6 035	18 302	3.0	44.1	5 850	15 561	2.7	86.9	6 465	21 069	4.2	56.0

addition. Whereas DRP accounted for only 5 to 16% of TP in runoff from unamended soils, it accounted for 46 to 83% of TP in runoff from corresponding dairy manure–amended soils. Furthermore, SS concentrations from unamended soils (929 to 1783 mg L^{-1}) were significantly higher ($p < 0.01$) than from dairy manure–amended soils (200 to 669 mg L^{-1}) for the Buchanan–Hartleton and Hagerstown soils, suggesting that the surface-applied dairy manure had effectively protected the soil from raindrop impact and erosion. The SS concentrations from unamended and dairy manure treatments were similar, however, for the Lewbeach soil (638–1922 mg L^{-1} for unamended, 889–2055 mg L^{-1} for dairy manure).

Runoff P concentrations from poultry manure– and swine slurry–treated soils were significantly greater than those from the dairy manure–treated soil for the Buchanan–Hartleton and Hagerstown soils (Fig. 2 and 3). For the Lewbeach soil, P concentrations in runoff from poultry and swine treatments were greater, but not significantly different than the dairy treatment. Runoff DRP concentrations from soils receiving surface application of poultry manure (4.4 to 12.5 mg L^{-1}) and swine slurry (6.7 to 13.9 mg L^{-1}) were not significantly different from each other (Fig. 2). Nor were differences in runoff TP concentrations from poultry manure– (13.1 to 22.4 mg L^{-1}) and swine manure–amended (11.1 to 23.4 mg L^{-1}) soils statistically significant (Fig. 3). Despite these similarities, erosion from poultry manure– and swine manure–amended soils did differ significantly for two of the soils. Suspended solids concentrations from poultry manure–amended soils (1140 to 1817 mg L^{-1}) were significantly higher ($p < 0.01$) than from swine slurry–amended soils (489 to 523 mg L^{-1}) for the Buchanan–Hartleton and Hagerstown soils.

Differences in erosion may be attributed to differences in the physical characteristics of these two manure sources. At the application rates used in this study, poultry manure covered less than one quarter of the soil surface (as determined through visual approximation) whereas the swine slurry effectively covered the entire soil surface. Relative differences in erosion rates appear to correspond with differences in the extent of soil cover. The fact that differences in erosion are not reflected in DRP and TP concentrations indicates the importance of surface-applied manure as the primary source of DRP and TP in runoff. Runoff P data reported on the basis of load result in the same general inferences as those drawn from concentration data (Table 3).

Runoff P concentrations from soils receiving surface application of DAP varied widely for DRP (1.7 to 18.3 mg L^{-1}) and TP (3.3 to 24.1 mg L^{-1}) alike. In high-P soils receiving surface application of DAP, P concentrations were higher than, but not significantly different from, corresponding poultry and swine manure treatments, and were significantly higher (except for TP concentration from the Lewbeach soil) than losses from soils receiving dairy manure (Fig. 2 and 3). In low-P soils, P concentrations following DAP addition were consistently lower than poultry and swine P losses, although the differences were only statistically significant in the Hagerstown soil (Fig. 2b and 3b), and were not significantly different than DRP losses from the dairy manure–amended Hagerstown and Lewbeach soils (Fig. 2b, 2c, 3b, and 3c).

Differences in runoff P concentrations among treatments were related to the water-soluble P content of the various sources. Runoff DRP concentrations were related to water-soluble P content of the P source, although the regression was poor when DAP was included ($r^2 = 0.22$, $p < 0.01$). When DAP was excluded from the analysis, the concentrations of water-soluble P in manure and DRP in runoff were linearly related across all soils, as described by a parallel lines model in which the regression slopes were statistically similar among soils but y intercepts differed ($r^2 = 0.86$, $p < 0.01$, $DRP^{0.5} = y$ intercept $+ 0.34 \times$ water-soluble P). Due to the fact that DRP comprises the major portion of TP loss from surface-treated soils, a similar model provided good description of the relationship between water-soluble P in the P sources and TP concentration in runoff ($r^2 = 0.78$, $p < 0.01$, $TP^{0.5} = y$ intercept $+ 0.33 \times$ water-soluble P). Elsewhere, Moore et al. (2000b) and Withers et al. (2001) observed DRP losses from P-amended soils that were proportional to the water-soluble P content of applied P sources. Results from this study reveal that water-soluble P content of manure can be an excellent indicator of the potential for surface-applied P sources to enrich runoff P.

Role of Initial Soil Phosphorus

Initial soil P concentration, as represented by Mehlich-3 P, modifies runoff P to various degrees. Although runoff P concentrations from low-P soils were less than from high-P members of the same soil, with the exception of one dairy manure treatment (Fig. 2a and 3a), differences were not always statistically significant. In the case of the unamended control soils, differences in runoff DRP may be attributed to differential desorption of P from low- and high-P soils while differences in runoff TP are a result of the concentration of P in eroded particles. Indeed, numerous studies have reported increases in runoff P losses with increasing soil P concentration (Sharpley, 1995; Pote et al., 1999).

In soils receiving surface application of P, however, the amendment, rather than the soil, serves as the major source of P in runoff. In these soils, differences in runoff P concentration associated with initial P may be attributed, in part, to varied buffering of DRP concentrations by intact soil and suspended sediment with differing P sorption characteristics. Soils with lower P sorption saturation (Table 1) have a higher affinity to sorb P from solution than do soils with high P sorption saturation (Kleinman et al., 2000). As DRP represents the major fraction of P in runoff from surface-amended soils, any process affecting DRP concentration also influences TP concentration. Significant differences in DRP and TP concentration related to initial P were evident for all treatments in the Hagerstown soils (Fig. 2 and 3). Across all soils, runoff P concentration following DAP application varied significantly with initial soil P. In addition, significant differences in DRP and TP loads were observed between low- and high-P Buchanan–Hartleton soils amended with poultry manure (Table 3).

Effect of Phosphorus Application Method

The method of P source application affects P loss (Fig. 1, 2, and 4). On average, following mixing, DRP accounted for 9% of runoff TP, whereas DRP accounted for 64% of TP in runoff from surface-applied soils. Losses of DRP from the unamended soils also averaged 9% of TP. In fact, across all soils and sources, DRP concentrations and loads following mixing of P sources with soil were not significantly different from the unamended soils.

Average runoff DRP concentrations from soils mixed with P sources were 5% of those from soil with surface-applied P sources. Due to the high runoff DRP concen-

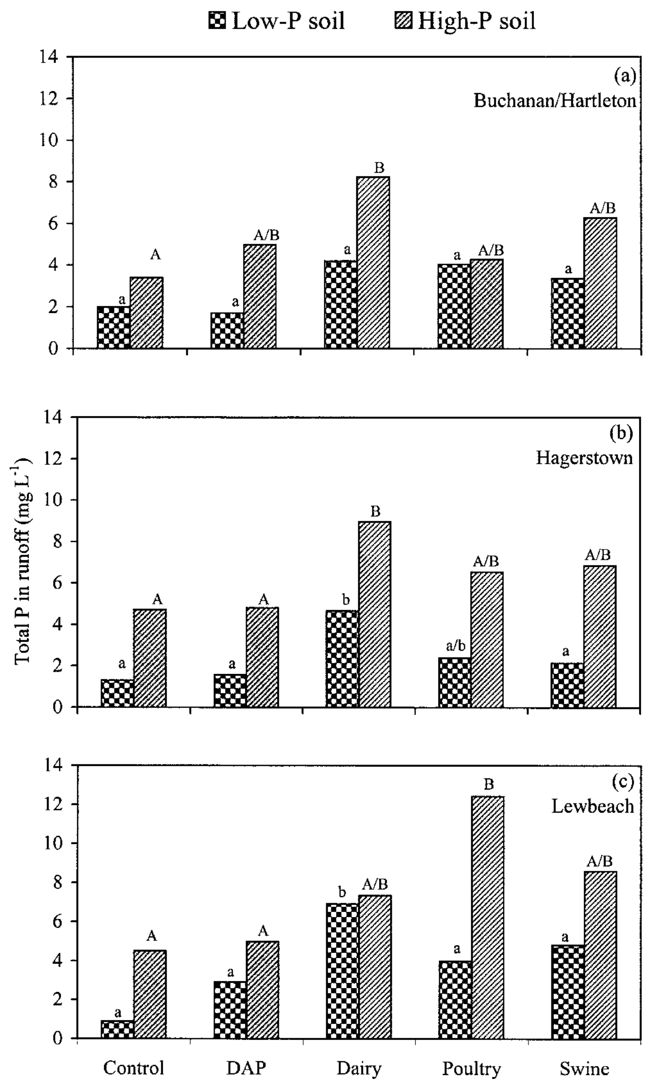

Fig. 4. Mean runoff total phosphorus (TP) concentrations following mixing of P sources with (*a*) Buchanan–Hartleton, (*b*) Hagerstown, and (*c*) Lewbeach soils. Letters above bars columns identify groupings of means that are not significant at $p = 0.05$, with lowercase denoting low-P soils and uppercase denoting high-P soils. Hypothesis tests were conducted on square root–transformed data.

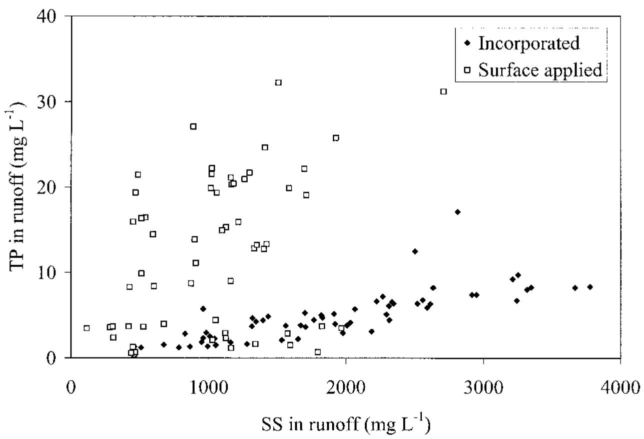

Fig. 5. Relationship of suspended solids (SS) and total phosphorus (TP) in runoff for surface-applied and mixed treatments.

trations from surface applications, TP concentrations in runoff following mixing averaged only 37% of those from surface-applied soils. At the same time, average SS concentrations in runoff from mixed soils were 200% of those from surface-applied soils. Whereas the correlation between SS and TP concentration was poor for surface-applied soils due to the overwhelming influence of DRP from the P sources ($r = 0.50$), the correlation between SS and TP concentration was relatively strong for the mixing treatment ($r = 0.80$) as erosion represented the dominant process of P transport (Fig. 5).

Thus, despite significantly higher erosion from mixed soils than from surface-applied soils ($p < 0.01$), runoff P losses were lower when P sources were mixed than when they were surface applied. Mixing decreases runoff P losses relative to surface application by decreasing the concentration of P at the soil surface. In addition, mixing promotes sorption of P released from the added sources, further reducing DRP losses. In this study, the accelerated erosion and associated particulate P loss induced by mixing were not as important to absolute TP losses as were elevated DRP losses associated with recent surface application. With time after application, the difference in P loss between surface applying and mixing amendments can be expected to decrease (Mueller et al., 1984).

Observations from this study are consistent with those of Mueller et al. (1984), who reported significant increases in runoff DRP losses from no-till soils following manure addition, but no significant change in runoff DRP losses from conventionally tilled soils following manure addition. In that study, more TP was lost in runoff from conventionally tilled soils than from no-till soils due to accelerated erosion under conventional tillage.

The magnitude of difference in P loss from surface-applied and mixed soils was modified by initial soil P concentration. In low-P soils, the difference between surface application and mixing averaged 6.0 mg DRP L^{-1} and 7.2 mg TP L^{-1}. In high-P soils, the difference averaged 10.8 mg DRP L^{-1} and 11.3 mg TP L^{-1}. On a percentage basis, the average difference in P loss between mixed and surface-applied sources from low-P soils was 67% (mg DRP L^{-1}) and 65% (mg TP L^{-1}) of high-P counterparts. Clearly, the higher P sorption capacities of the low-P soils sufficiently reduced absolute P loss to affect relative differences in P loss related to application method.

A final modifying effect of application method on P loss was on runoff quantity. Runoff volumes are presented in Table 3. While surface application of DAP and poultry manure did not provide sufficient soil cover to affect infiltration at the application rates simulated in this study, significant differences in runoff volume were apparent between surface-applied and mixed dairy manure and swine slurry treatments. Specifically, runoff volumes were significantly higher following mixing for three of the six dairy manure treatment combinations and for two of the six swine slurry treatment combinations. Differences in runoff volume, however, were not manifest in significant differences in P loads, as they were not sufficient to offset differences in runoff DRP concentration between and mixed and surface-applied sources.

CONCLUSIONS

Quantification of P losses from manure-amended soils is necessary to develop nutrient management strategies that protect water quality. In this study, runoff DRP concentrations were highly correlated with water-soluble P concentration of surface-applied manure. This relationship supports the use of water-soluble P in manure as an indicator of P loss potential, providing an effective surrogate for resource-intensive runoff studies to validate source variables in P site assessment indices. Results from this study also confirm the effect application method can have on runoff P loss. In areas where transfers of DRP are of particular concern, immediate incorporation of P sources may be prudent. Finally, observed interactions between initial soil P and runoff DRP concentration show that practices that increase P sorption at the soil surface, such as prudent management of soil test P, deep tillage (Sharpley, 1999), and addition of P-sorbing materials (Stout et al., 1998; Moore et al., 2000a) may reduce P loss in surface runoff, even after surface application has occurred.

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