Determination of Phosphorus Source Coefficients for Organic Phosphorus Sources: Laboratory Studies

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ABSTRACT

Phosphorus losses in runoff from application of manures and bio-solids to agricultural land are implicated in the degradation of water quality in the Chesapeake and Delaware Inland Bays. We conducted an incubation study to determine the relative P solubility and bioavailability, referred to as P source coefficients (PSCs), for organic P sources, which are typically land-applied in the Mid-Atlantic USA. Nine organic and one inorganic (KH₂PO₄) P amendments were applied to an Evesboro loamy sand (mesic, coated Typic Quartzipsamments) at a rate of 60 mg P kg⁻¹ and incubated for 8 wk with subsamples analyzed at 2 and 8 wk. There was an increase in Mehlich-3 P (M3-P), water-soluble P (WS-P), iron-oxide strip extractable P (FeO-P), and Mehlich-3 P saturation ratio (M3-PSR) with P additions, which varied by P source. The trend of relative extractable WS-P, FeO-P, and M3-P generally followed the pattern: inorganic P > liquid and deep pit manures > manures and biosolids treated with metal salts or composted. We found significant differences in the availability of P from varying organic P sources. The use of PSCs may be beneficial when determining the risk of P losses from land application of manures and other organic P sources and could be used in risk assessments such as a P site index. These PSCs may also be useful for determining P application rates when organic P sources are applied to P deficient soils for use as a fertilizer source.

$\mathbf{P}$HOSPHORUS LOSSES in runoff from agricultural fields are implicated in the degradation of water quality in the Chesapeake Bay, its tributaries, and other surface waters in the Mid-Atlantic region (e.g., Delaware's Inland Bays) (Ritter, 1986, 1992; Sims and Coale, 2002). Concerns about nonpoint source pollution of surface and shallow ground waters by P stimulated efforts to develop practical risk assessment tools to identify the agricultural fields in a watershed most susceptible to P loss. The most widely used approach in the USA today is the phosphorus site index (PSI), which evaluates the relative risk of P loss to water from fields based on site characteristics that affect P transport, the type of P source applied, and soil and crop management practices. There are presently at least three states (Delaware, DE; Maryland, MD; and Pennsylvania, PA) that have incorporated a weighting coefficient for organic P sources into their PSI to reflect the differences in P solubility of these materials.

One aspect of the DE–MD PSI that remains unresolved is the recommended use of a PSC to differentially weight the risk of P loss based on the properties of the organic P source applied at the site. The PSC concept was included because past research shows that the solubility of P in fertilizers, organic P sources, and soils amended with these materials differs widely. Sharpley and Moyer (2000) determined that the cumulative amount of P leached from columns after five simulated rainfall events differed significantly between organic P sources, and that the water-extractable P content of the material provided a good estimate of the P lost through leaching. Runoff dissolved reactive P (DRP) concentrations from simulated rainfall experiments were also found to be closely related with WS-P concentrations in surface applied manures (Kleinman et al., 2002). Manures or biosolids treated with metal salts [i.e., FeCl₃ or Al₂(SO₄)₃] or metal by-products (Al or Fe wastewater treatment residuals) generally have less soluble P than untreated manures or biosolids, and therefore a lower risk of P losses (Codling et al., 2000; Dao et al., 2001; Elliott et al., 2002; Penn and Sims, 2002; Sims and Luka-McCafferty, 2002). Moore et al. (2000) found significantly lower DRP in runoff from pastures receiving alum-treated poultry litter than untreated poultry litter. Thus, to fairly assess the risk of P loss, a weighting factor (the PSC) should be used that reflects the relative solubility and/or bioavailability of the P source applied. At present, the same default PSC value is used in the DE–MD PSI for all P sources (fertilizers, manures, biosolids) because of a lack of adequate research evaluating this concept on soils in the region. Therefore, our objective in this study was to determine relative P solubility and bioavailability for a wide range of organic P sources commonly used in land application programs in the Mid-Atlantic USA.

MATERIALS AND METHODS

Soil and Organic By-Product Collection and Characterization

The soil used in this study was an Evesboro loamy sand collected from the 0- to 20-cm depth from a farm in Sussex County, DE. After sampling, the soil was air-dried and sieved

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Abbreviations: BL, broiler litter; BLA, broiler litter with alum; BP, Blue Plains; BR, Back River; DE, Delaware, DBC, dairy/beef compost; DBL, dairy/beef liquid; DBS, dairy/beef solid; DRP, dissolved reactive phosphorus; FeO-P, iron-oxide strip extractable phosphorus; ICP–AES, inductively coupled plasma atomic emission spectroscopy; LP, Little Patuxent; M3-P, Mehlich-3 extractable phosphorus; M3-PSR, Mehlich-3 phosphorus saturation ratio; MD, Maryland; PA, Pennsylvania; PDP, poultry—deep pit; PSC, phosphorus source coefficients; PSI, phosphorus site index; RPE, relative phosphorus extractability; SF, swine—fresh; SL, swine—liquid; TP, total phosphorus; WS-P, water soluble phosphorus; WWTP, wastewater treatment plant.

through a 2-mm screen and analyzed by standard methods of the University of Delaware Soil Testing Laboratory (Sims and Heckendorn, 1991). Results of these analyses showed the soil was typical of the coarse-textured, acidic, low organic matter soils of the U.S. Atlantic Coastal Plain. It had a pH of 6.0, an organic matter content of 12.0 g kg^{-1}, silt and clay contents of 110 and 70 g kg^{-1} respectively, and soil test P (Mehlich 3) concentration of 33 mg kg^{-1}, a concentration where P fertilizer additions would be recommended in Delaware.

We used nine different organic P amendments in this study, including a range of animal manures and municipal biosolids. There were three different sources for each type of amendment except for the broiler litter (BL), which had four sources and the biosolids where there was only one source for each type, for a total of 28 organic P sources (Table 1). Most of the animal manures were provided by the University of Maryland Soil and Manure Testing Laboratory, which had received them from farmers requesting nutrient analyses. Exceptions included one BL (BL-4) and the three alum-amended BL samples (BLA 1, 2, 3), which, along with the three biosolids were obtained from the University of Delaware. The three biosolids used in the study received different treatments that could potentially affect P solubility, and were treated as follows: Blue Plains (BP; lime-stabilized [CaO] with FeCl$_3$ added in the wastewater treatment plant process [WWTP]), Back

Table 1. Total and water-soluble P (WS-P) concentrations (on a dry weight basis) in the 28 organic P sources used in the incubation study

Organic P Source	WS-P	Total P	WS-P to Total P
	——— mg kg^{-1} ———		%
Dairy/Beef liquid (DBL)			
1	915	8 334	11.0
2	186	11 620	1.6
3	1 108	8 807	12.6
Dairy/Beef semisolid (DBS)			
1	1 110	4 469	24.8
2	326	1 350	24.1
3	405	2 218	18.2
Dairy/Beef compost (DBC)			
1	83	6 162	1.3
2	528	9 741	5.4
3	250	7 979	3.1
Swine–liquid (SL)			
1	7 404	20 125	36.8
2	10 268	17 212	59.7
3	10 662	27 840	38.3
Swine–fresh (SF)			
1	6 025	12 474	48.3
2	1 095	8 479	12.9
3	8 365	16 268	51.4
Poultry–deep pit (PDP)			
1	5 331	40 789	13.1
2	4 851	25 959	18.7
3	6 061	26 714	22.7
Broiler litter (BL)			
1	3 300	20 000	16.5
2	2 240	18 400	12.2
3	4 858	21 500	22.6
4	3 049	20 600	14.8
Broiler litter with alum (BLA)			
1	1 537	19 700	7.8
2	1 192	21 200	5.6
3	1 251	17 400	7.2
Biosolids			
BP	357	14 300	2.5
LP	138	14 000	1.0
BR	108	35 000	0.3

River (BR; anaerobically digested with FeCl$_3$ added in the WWTP), and Little Patuxent (LP; lime stabilized [CaO]).

The manures and biosolids were dried at 60°C, ground to pass a 0.8-mm screen in a stainless steel Wiley mill, and analyzed for (i) total P (TP) by microwave-assisted digestion of a 0.5-g dried sample with 7 mL of concentrated HNO$_3$ and 3 mL of 30% (v/v) H$_2$O$_2$, and (ii) WS-P: (1:10 weight to volume using deionized water, shaken for 1 h, and filtered with a 0.45-μm Millipore [Billerica, MA] membrane). The acid digests and water extracts were analyzed for P by inductively coupled plasma atomic emission spectroscopy (ICP–AES).

Incubation Study

Each of the 28 organic P sources was incorporated (three replications of each source) with the Evesboro soil at a rate of 60 mg P kg^{-1}, equivalent to approximately 135 kg P ha^{-1}, a P application rate representative of that made when manures are applied to meet crop N requirements. An inorganic P source (KH$_2$PO$_4$), applied at the same P rate, represented commercial fertilizer P and a control (unamended soil) was included. After incorporation, the soils were incubated in 250-mL polyethylene containers in the laboratory at room temperature (25 ± 2°C) and 80% of field capacity in a completely randomized design. Two holes were made in the tops of the incubation containers to allow gas exchange and prevent anaerobic conditions during the incubation. Soil moisture content was maintained by adding deionized water at weekly intervals.

Subsamples of the incubation soil mixtures were analyzed at 2 and 8 wk after the initiation of the study as follows: (i) WS-P: (1:10, soil to deionized water, shaken for 1 h, filtered with a 0.45-μm Millipore membrane); (ii) FeO-P (1:40, soil to 0.01M CaCl$_2$ + Fe-oxide coated filter paper strip, shaken for 16 h, followed by dissolving P from the filter paper strip for 1 h in 1M H$_2$SO$_4$; Chardon et al., 1996); and (iii) M3-P (1:10, soil to 0.2M CH$_3$COOH + 0.25M NH$_4$NO$_3$ + 0.015M NH$_4$F + 0.13M HNO$_3$ + 0.001M EDTA) (Mehlich, 1984). All soil extracts were measured by ICP–AES. The M3-PSR (Sims et al., 2002) was calculated as follows (values for P, Al, and Fe in mmol kg^{-1}):
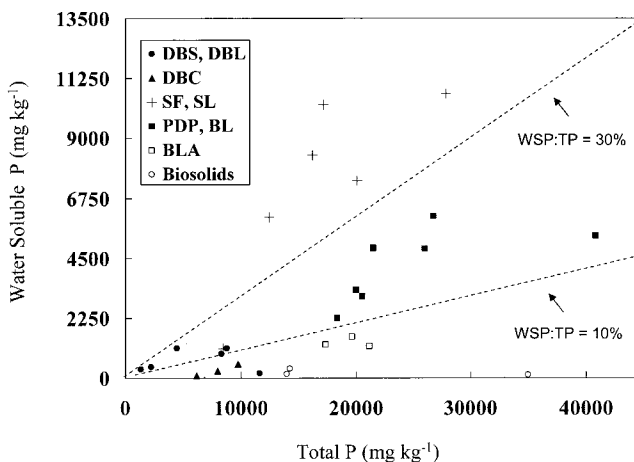

Fig. 1. Relationship between water-soluble P (WS-P) and total P in the 28 organic P sources. Dashed lines indicate WS-P values that are 10 or 30% of total P concentrations. DBS, dairy/beef solid; DBL, dairy/beef liquid; DBC, dairy/beef compost; SF, swine–fresh; SL, swine–liquid; PDP, poultry–deep pit; BLA, broiler litter with alum.

$$M3\text{-}PSR = M3\text{-}P/(M3\text{-}Al + M3\text{-}Fe)$$

Calculation of Phosphorus Source Coefficients

In the context of this paper, a PSC is a quantitative laboratory estimate of the relative solubility and bioavailability for soils amended with organic P sources, compared with soils amended with fertilizer P. The relative solubility of P is measured by extraction of WS-P and determination of easily desorbed P (FeO-P) and bioavailability is assessed with an agronomic soil P test (Mehlich 3).

Approach for Laboratory Estimation of Phosphorus Source Coefficients

We used the following approach to calculate PSC values for the 28 organic by-products evaluated in our incubation study and suggest consideration of this approach as a standardized method to estimate PSC values.

1) At each time interval (2 and 8 wk) we calculated the extractability of P in soils amended with the organic and inorganic P (Soil $P_{OPS/IPS}$) sources by three soil P tests (WS-P, FeO-P, and M3-P) as follows:

Extractability of P (%) =

$$\frac{(\text{Soil } P_{OPS/IPS} - \text{Soil } P_{Control}, \text{mg P kg}^{-1}) \times 100}{(\text{Total P added} = 60 \text{ mg P kg}^{-1})}$$

2) We then calculated, for each soil P test, a relative P extractability (RPE) at each sample date by normalizing P extractability for each organic P sources relative to

the inorganic P source used in this study (KH_2PO_4). By definition, this assigns a RPE value of 100% to the inorganic P source:

$$RPE = (P \text{ extractability}_{OPS})/(P \text{ extractability}_{IPS}) \times 100$$

The RPE is equivalent to the PSC of an organic P source, unless additional weighting factors are used in calculating the PSC for a given PSI.

Statistical Analyses

All statistical analyses of the data in this study were performed using the PROC GLM (general linear models) procedure of the Statistical Analysis System (SAS Institute, 2002). The least significant difference (LSD) method, with a probability value of 0.05, was used to determine significant differences between treatment means. Relationships significant at the 0.05, 0.01, and 0.001 probability levels are marked in the text as *, **, ***, respectively.

RESULTS AND DISCUSSION

Properties of the Organic Phosphorus Sources

Total P concentrations in the 28 organic P sources (Table 1) ranged from a low of 1350 mg kg^{-1} for a dairy/beef solid (DBS) manure to a high of 40 789 mg kg^{-1} for a poultry—deep pit (PDP) manure and were reasonably consistent with concentrations reported for these types of organic P sources (Sharpley et al., 1998; Evanylo, 1999; Stehouwer et al., 2000). Within animal species we observed a trend for higher TP concentrations in liquid

Table 2. Effect of P source on Mehlich-3 P, iron-oxide strip extractable P (FeO-P), and water-soluble P (WS-P) after a 2- and 8-wk incubation in an Evesboro loamy sand soil after addition of 60 mg P kg^{-1}.

P Source†	Mehlich-3 P		FeO-P		WS-P	
	Week 2	Week 8	Week 2	Week 8	Week 2	Week 8
			mg kg^{-1}			
Unamended soil	33	29	1.0	0.2	0.2	0.4
KH$_2$PO$_4$	93	83	28.8	17.8	9.0	6.2
DBL-1	67	61	19.5	14.8	6.5	5.1
DBL-2	78	61	18.9	16.3	5.4	4.4
DBL-3	70	84	26.4	23.1	10.5	8.2
DBS-1	76	54	14.3	8.2	5.4	4.8
DBS-2	74	61	17.8	12.0	8.4	7.4
DBS-3	97	65	15.5	12.4	4.5	3.9
DBC-1	64	55	15.3	9.7	2.4	1.7
DBC-2	57	60	16.6	12.4	5.2	2.2
DBC-3	47	45	8.0	5.5	1.5	1.3
SL-1	82	71	18.7	14.5	8.8	5.7
SL-2	105	94	31.9	24.0	15.9	4.2
SL-3	82	72	23.2	17.3	7.6	3.2
SF-1	77	72	16.3	13.8	5.6	2.7
SF-2	74	70	18.6	14.4	5.1	2.1
SF-3	84	76	19.8	16.8	7.0	2.5
PDP-1	84	75	28.3	22.4	5.7	4.1
PDP-2	81	73	21.1	16.2	4.3	2.7
PDP-3	95	83	21.2	19.2	8.3	2.8
BL-1	67	59	10.2	9.2	4.6	2.0
BL-2	68	59	10.5	8.1	3.9	1.8
BL-3	65	61	11.5	9.5	4.5	2.1
BL-4	62	61	12.6	9.2	2.2	1.5
BLA-1	64	62	6.4	5.4	1.9	0.7
BLA-2	64	62	4.6	5.1	1.0	0.6
BLA-3	69	62	6.2	5.6	0.9	0.6
BP	64	58	15.4	9.5	1.0	2.8
LP	80	65	17.7	15.6	2.7	3.5
BR	48	44	4.5	6.3	0.4	0.8
LSD$_{0.05}$	8	6	4.4	3.6	1.7	1.4

† DBL, dairy/beef liquid; DBS, dairy/beef semisolid; DBC, dairy/beef compost; SL, swine–liquid; SF, swine–fresh; PDP, poultry–deep pit; BL, broiler litter; BLA, broiler litter with alum; BP, Blue Plains; LP, Little Patuxent; BR, Back River; LSD, least significant difference. Differences between means greater than the LSD indicates significant differences at $P < 0.05$.

dairy, beef, and swine manures and the PDP manure (no bedding) than in solid or semi-solid manures of the same species.

Water-soluble P in the organic P sources ranged from 83 to 10 662 mg kg^{-1} and was highest in liquid (SL) and fresh swine (SF) manures and the PDP manure (Table 1). Total and WS-P were poorly correlated ($r = 0.47$), thus knowledge of TP in organic P sources would be of limited value as a means to estimate WS-P. However, it may be possible, with a larger database, to develop reasonably accurate estimates of the expected ranges for WS-P by type of organic source based on a TP analysis. The percentage of TP in a soluble form ranged from 0.3% (BR) to 59.7% (SL-2) and, based on averages for each type of organic P source, could be grouped into three WS-P to TP categories: (i) <10%: DBC, DBL, BLA, and biosolids; (ii) 10 to 30%: DBS, PDP, BL; and (iii) > 30%: SF and SL manures (Fig. 1). There was a great deal of variability within some of the organic P source groups, for example the WS-P to TP for DBL-2 was only 1.6 compared with approximately 12 for the other samples in the group and SF-2 was 12.9 compared with approximately 50 for the other samples in the group, therefore these generalizations should be interpreted with caution.
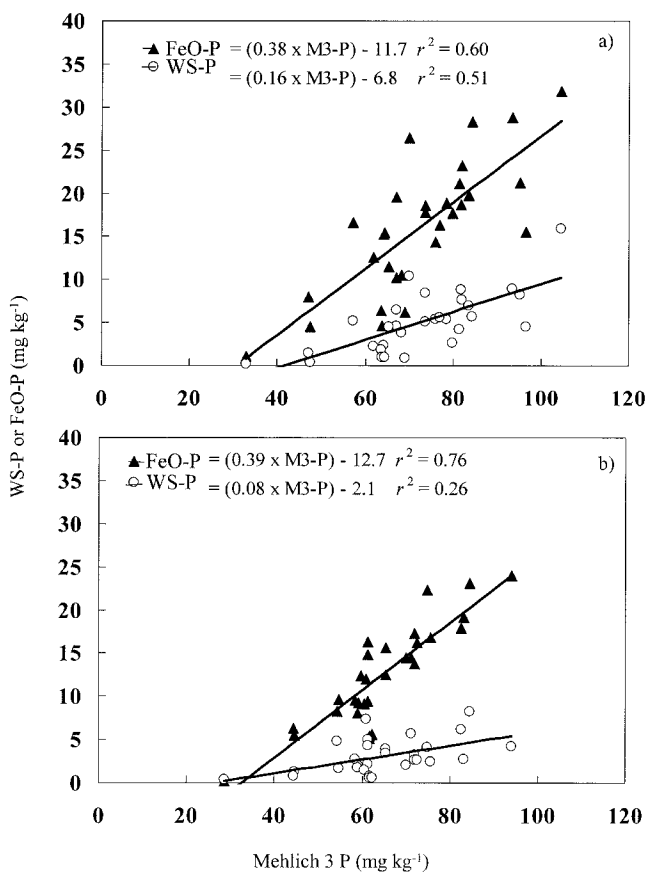
Fig. 2. Relationship between soil test P (Mehlich 3) and water-soluble P (WS-P) or iron-oxides strip extractable P (FeO-P) following addition of 28 organic P sources at (a) 2 and (b) 8 wk.

Effect of Organic By-Products on Extractable Soil Phosphorus

Amending the soil with equal amounts of P (60 mg P kg^{-1}) as organic by-product or KH_2PO_4 increased all forms of extractable soil P at both sample dates, but the amount of the increase varied with P source (Table 2). For example, adding P from any source consistently increased soil test P (M3-P) from the "medium" (25–50 mg M3-P kg^{-1}) agronomic rating category in the unamended soil to the "optimum" (50–100 mg M3-P kg^{-1}) category (Table 2). However, the actual M3-P in the amended soils ranged from 48 to 105 mg kg^{-1} at 2 wk and 44 to 94 mg kg^{-1} at 8 wk (Table 2). Soil test P (M3-P) was significantly correlated with FeO-P at both sample dates and regression equations between these two variables could account for 60 and 76% of the variability in this relationship (Fig. 2). However, M3-P could not predict WS-P as accurately, particularly at the 8-wk sample date ($r^2 = 0.26$, NS; Fig. 2).

We also observed that all forms of extractable P and the percentage of TP that could be recovered tended to decrease with time, which likely reflects sorption by the soil of added soluble P and some of the P released by mineralization of organic P. Overall average values (and percentage of total added P recovered) for M3-P, FeO-P, and WS-P at 2 wk were 72 (68%), 16 (28%), and 5.0 (8%) mg kg^{-1} compared with 65 (62%), 12 (25%), and 3.1 (5%) mg kg^{-1} at 8 wk (Tables 2 and 3).

Effect of Organic By-Products on Soil pH, Aluminum, Iron, Calcium, and Phosphorus Saturation

Amending the soil with organic by-products affected soil pH and, in some cases, the concentrations of soil Al, Fe, and Ca, soil properties that influence P solubility (Table 4); these changes were similar for the 2- and 8-wk samples. At the conclusion of the 8-wk incubation, soil pH ranged from 4.55 to 7.59 in amended soils, compared with pH 5.50 in the unamended soil. In most cases, adding organic by-products increased soil pH. Exceptions included the BL samples, especially those amended with alum, and the BR biosolid where pH decreased relative to the control. This pH drop could be explained, in the BLA samples, by the fact that these by-products were amended with metal salts known to acidify soils [e.g., $Al_2(SO_4)_3$]. At the end of the 8-wk incubation, soil pH was significantly correlated with WS-P ($r = 0.71$***) and M3-Ca ($r = 0.72$***). These correlations are consistent with the well-known positive effects of increasing pH on soil P availability and also suggest the presence of residual lime or Ca in some of the organic by-products, perhaps from lime used in animal feed or in waste treatment processes, such as the BP and LP biosolids where lime is known to be added at the WWTP. Soil Mehlich-3 Fe concentrations were significantly greater only with addition of the BP and BR biosolids, materials generated using Fe salts at the WWTP. None of the by-products, even the alum-treated broiler litters (BLAs), significantly increased soil Mehlich-3 Al.

Table 3. Percentage of added P extracted by Mehlich-3 P, FeO-P, and WS-P after a 2- and 8-wk incubation in an Evesboro loamy sand soil.

	Mehlich-3 P		FeO-P		WS-P	
P Source	Week 2	Week 8	Week 2	Week 8	Week 2	Week 8
			%			
KH_2PO_4	101	89	46	29	15	10
DBL-1	57	54	31	24	10	8
DBL-2	76	54	30	27	9	7
DBL-3	62	92	42	38	17	13
DBS-1	72	42	22	13	9	7
DBS-2	68	53	28	20	14	12
DBS-3	106	61	24	20	7	6
DBC-1	52	43	24	16	4	2
DBC-2	40	51	26	20	8	3
DBC-3	23	26	12	9	2	2
SL-1	81	70	29	24	14	9
SL-2	119	108	51	40	26	6
SL-3	82	71	37	28	12	5
SF-1	73	72	25	23	9	4
SF-2	68	68	29	24	8	3
SF-3	84	78	31	28	11	4
PDP-1	86	76	45	37	9	6
PDP-2	81	73	33	27	7	4
PDP-3	104	90	34	32	13	4
BL-1	57	50	15	15	7	3
BL-2	59	50	16	13	6	2
BL-3	54	54	18	15	7	3
BL-4	48	53	19	15	3	2
BLA-1	51	55	9	9	3	1
BLA-2	51	54	6	8	1	0.4
BLA-3	60	55	9	9	1	0.4
BP	52	49	24	16	1	4
LP	78	61	28	26	4	5
BR	24	26	6	10	0.3	1

† DBL, dairy/beef liquid; DBS, dairy/beef semisolid; DBC, dairy/beef compost; SL, swine–liquid; SF, swine–fresh; PDP, poultry–deep pit; BL, broiler litter; BLA, broiler litter with alum; BP, Blue Plains; LP, Little Patuxent; BR, Back River.

Table 4. Effect of P source on soil pH, Mehlich-3 Al, Fe, and Ca and Mehlich-3 saturation ratio (M3-PSR) after an 8-wk incubation in an Evesboro loamy sand soil.

Organic P Type†	pH	M3-Al	M3-Fe	M3-Ca	M3-PSR
			mg kg^{-1}		
Unamended soil	5.50	511	103	108	0.045
KH_2PO_4	5.51	525	111	144	0.124
DBL-1	6.42	434	98	223	0.111
DBL-2	6.21	457	101	219	0.105
DBL-3	6.59	483	112	276	0.137
DBS-1	6.68	461	104	236	0.093
DBS-2	6.86	426	86	304	0.113
DBS-3	5.71	496	110	235	0.103
DBC-1	6.22	456	103	383	0.094
DBC-2	6.04	462	102	209	0.102
DBC-3	5.58	495	111	224	0.071
SL-1	5.93	506	111	169	0.111
SL-2	6.21	497	112	216	0.149
SL-3	5.81	495	106	148	0.115
SF-1	5.21	510	112	170	0.111
SF-2	5.98	495	108	274	0.111
SF-3	5.73	504	109	169	0.118
PDP-1	5.52	492	108	263	0.120
PDP-2	6.38	509	109	385	0.113
PDP-3	6.27	498	110	345	0.131
BL-1	5.25	466	94	156	0.101
BL-2	5.20	450	94	151	0.104
BL-3	5.49	473	99	157	0.102
BL-4	5.04	504	105	165	0.095
BLA-1	4.96	515	100	165	0.095
BLA-2	4.96	518	101	281	0.095
BLA-3	4.55	530	101	168	0.094
BP	6.61	454	166	560	0.095
LP	7.59	449	103	732	0.114
BR	5.06	471	127	119	0.073
LSD$_{0.05}$	0.22	35	7	64	0.005

† DBL, dairy/beef liquid; DBS, dairy/beef semisolid; DBC, dairy/beef compost; SL, swine–liquid; SF, swine–fresh; PDP, poultry–deep pit; BL, broiler litter; BLA, broiler litter with alum; BP, Blue Plains; LP, Little Patuxent; BR, Back River; LSD, least significant difference. Differences between means greater than the LSD indicates significant differences at $P < 0.05$.

The addition of all P sources also increased soil P saturation (M3-PSR) from 0.045 in the unamended soil to 0.073 for the BR biosolids and a high of 0.149 with SL-2 manure (Table 4). This increase in M3-PSR is due to the significant increases in extractable M3-P from P additions without a concomitant increase in extractable Fe and Al, due to the small amount of these metals added relative to the amount already present in the soil. By way of comparison, Sims et al. (2002) reported that a M3-PSR of 0.15 corresponded to a soil P saturation used as environmental P thresholds in the USA and Europe. For many of these organic amendments one

Table 5. Correlation coefficients between forms of P in the organic by-products and forms of soil P after a 2- and 8-wk incubation.

	Form of Organic By-Product P		
Soil P fractions‡	Total P	WS-P	WS-P to Total P
		r	
	Time: 2 wk		
M3-P	−0.27ns	0.43*	0.56**
FeO-P	−0.35ns	0.36*	0.44*
WS-P	−0.21ns	0.57**	0.70***
M3-PSR	−0.39*	0.31ns	0.47*
	Time: 8 wk		
M3-P	−0.11ns	0.52**	0.57**
FeO-P	−0.21ns	0.35ns	0.41*
WS-P	−0.47*	0.07ns	0.28ns
M3-PSR	−0.22ns	0.44*	0.52*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Not significant.
‡ M3-P, Mehlich-3 P; FeO-P, iron-oxide strip extractable P; WS-P, water-soluble P; M3-PSR, Mehlich-3 P saturation ratio.

Table 6. Relative soil P extractability, based on Mehlich-3 P, iron-oxide strip extractable P (FeO-P), and water-soluble P (WS-P), after a 2- and 8-wk incubation of organic P sources in an Evesboro loamy sand soil.

Organic P Source	Mehlich-3 P		FeO-P		WS-P	
	Week 2	Week 8	Week 2	Week 8	Week 2	Week 8
	%					
DBL-1	56	61	67	86	72	79
DBL-2	76	60	64	95	59	69
DBL-3	62	104	92	131	118	135
DBS-1	71	48	48	46	60	77
DBS-2	67	60	60	69	95	122
DBS-3	106	68	52	71	49	61
DBC-1	52	48	51	54	24	22
DBC-2	40	58	56	70	57	32
DBC-3	24	30	25	31	14	16
SL-1	81	79	64	81	98	91
SL-2	119	122	111	140	181	67
SL-3	81	81	80	98	85	49
SF-1	73	81	55	79	62	39
SF-2	67	77	63	82	56	29
SF-3	84	88	68	98	78	37
PDP-1	85	86	97	127	63	64
PDP-2	80	82	73	91	46	40
PDP-3	103	101	73	109	96	42
BL-1	57	57	33	52	50	27
BL-2	58	56	34	47	41	24
BL-3	54	61	38	53	49	31
BL-4	48	59	41	53	23	18
BLA-1	51	62	19	30	18	7
BLA-2	51	61	13	28	9	4
BLA-3	60	62	19	31	7	4
BP	52	55	51	54	8	42
LP	77	68	59	89	27	52
BR	24	29	13	38	1	8
LSD$_{0.05}$†	15	12	16	22	22	25

† DBL, dairy/beef liquid; DBS, dairy/beef semisolid; DBC, dairy/beef compost; SL, swine–liquid; SF, swine–fresh; PDP, poultry–deep pit; BL, broiler litter; BLA, broiler litter with alum; BP, Blue Plains; LP, Little Patuxent; BR, Back River; LSD, least significant difference. Differences between means greater than the LSD indicates significant differences at $P < 0.05$.

application resulted in an increase in M3-PSR, which would be considered to be an environmental concern.

Relationships between Phosphorus Concentrations in Organic Phosphorus Sources and Soil Phosphorus

One objective of this research was to determine if simple tests for P in the organic P sources, such as TP, WS-P, or the WS-P to TP ratio could accurately predict changes in extractable soil P over time. The TP concentration in the organic P sources was a very poor predictor of soil P fractions at both sample dates (Table 5). The WS-P content of the organic sources was a marginal predictor of extractable P at 2 wk and a poor predictor at 8 wk. The best predictor of soil WS-P at 2 wk following treatment application was the WS-P to TP ratio of the organic P source, this predictor was similar at 8 wk for all but WS-P, which was insignificant at this time. However, this ratio only explained 17 to 49% of the variability between P in the organic P sources and soil extractable P (Table 5). Measurements of the P in the organic sources were poor predictors of extractable P and were not consistent for both sampling dates. Therefore measures of P extractability of organic P sources may have limited value in predicting losses from soils when the materials are incorporated.

Relative Phosphorus Extractability for Organic Phosphorus Sources

The relative P extracted in the added in the organic P sources, compared with inorganic P varied widely

among P sources and for all soil P tests evaluated (Table 6). In general, with only a few exceptions, P added in the organic sources was less extractable than KH_2PO_4 as evidenced by the fact that most RPEs were <100%. The most striking exceptions included some of the liquid and deep pit manures that consistently had RPE near or >100% for one or more forms of soil P. The change in RPE between the 2- and 8-wk sampling dates was only significant in 64, 43, and 54% of the M3-P, FeO-P, and WS-P samples, respectively, and trends were only examined for those samples with significant differences. There was little change in RPE for the agronomic soil test (M3-P) for the organic by-products between the 2- and 8-wk sampling dates (Fig. 3a), with a few samples having lower M3-P. The RPE based on FeO-P tended to increase slightly with time between the two sampling dates (Fig. 3b). The RPE based on WS-P had increases in only two treatments (DBL-3 and BP) while the rest of the treatments had a decrease in WS-P (Fig. 3c and Table 6). The increase in WS-P of the BP treatment may be due to the fact that the biosolid was lime stabilized and the addition of the material to a slightly acidic soil may have released some of the Ca–P complexes.

We averaged the RPEs by type of organic P source and sorted them in ascending order for each soil P test and sample date to determine if they could be grouped into risk categories based on the relative extractability of soil P (Fig. 4). While the rankings varied slightly between soil P tests and incubation times, the general trend observed was that liquid and deep pit manures

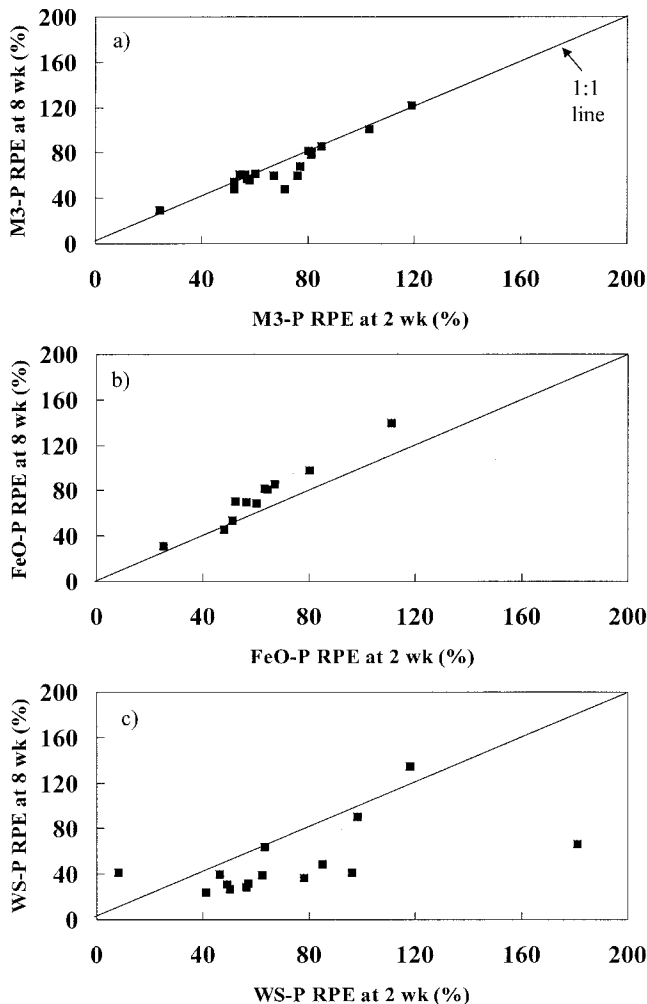J. ENVIRON. QUAL., VOL. 33, JANUARY–FEBRUARY 2004

Fig. 3. Relationship between relative extractable soil (a) Mehlich 3-P, (b) iron-oxide strip extractable P (FeO-P), and (c) water-soluble P (WS-P) at 2 and 8 wk after treatment incorporation (for those samples that were significantly different between the two dates). The 1:1 line represents points in each relationship where no change in relative extractable P occurred between 2 and 8 wk.

had the highest RPE and the organic P sources treated with metal salts (BLA and BR) and the composted manure (DBC) had the lowest (Fig. 4). The individual RPE values were then averaged for all soil tests at all times by organic P category to obtain an overall RPE for each organic P source (Fig. 5). The best predictor of the overall RPE for the organic sources was the FeO-P at 2 wk, having an $r^2 = 0.89$*** (Fig. 6).

These general trends in P availability are consistent with the results of other researchers who examined P availability and losses in runoff and leaching from different P sources. Sharpley and Moyer (2000) examined P leaching from six organic P sources. The cumulative P leached after five consecutive rainfall simulations ranged from 1912 to 5911 mg P kg^{-1} material, and followed the general trend: poultry deep pit manures and swine slurry had the greatest P leaching followed by poultry litters and dairy manure/compost with the least amount leached from the poultry compost. Siddique et al. (2000) found that the cumulative P leached from

columns decreased in the order: P fertilizer > sludge > control. Maguire et al. (2001) found that the trend in soil extractable WS-P, FeO-P, and Mehlich-1 P followed the pattern: soils amended with biosolids produced without the use of Fe or Al > poultry litter and biosolids produced using Fe or Al and lime > biosolids produced using only Fe and Al salts. These results clearly show that the relative solubility and bioavailability of P in soils amended with organic P sources should be considered when assessing the risk of nonpoint P pollution of surface and shallow ground waters.

These results may also have implications from an agronomic standpoint when organic P sources are used as a fertilizer on low P soils. The RPE of the organic sources decreased as the strength of the soil extractant increased, with Mehlich 3 giving the least differences in RPE among the sources. This suggests that plants may be able to obtain similar P uptake from the organic P sources, although those sources treated with metal salts would probably still be less available for plant uptake. To efficiently use organic source materials as a P fertilizer, these differences in RPE should be taken into account and used to determine the appropriate application rates for these sources to meet plant P requirements.

CONCLUSIONS

The data from this study suggest that there are significant differences between the solubility and bioavailability of organic P sources typically land applied in the Mid-Atlantic region. These differences may warrant differentiation of these sources in risk assessment tools such as the PSI, as well as in nutrient management recommendations when these materials are used as the sole source of P fertilizer. The best predictor of overall RPE was the FeO-P of the amended soils 2 wk after treatment incorporation, which may provide an easy test for labs to use to determine P solubility of various materials.

Phosphorus sorption properties vary widely among different soils and RPE derived from soil incubation studies such as we conducted will be strongly influenced by the soil(s) used. Since most laboratories conducting analyses of organic P sources will have only limited information, at best, about the P sorption properties of the soil to which the organic P source being analyzed will be applied, some direct measure of P solubility in the organic P source (e.g., WS-P) would be the easiest approach to incorporate into PSI evaluations. This approach might be suitable to assess the risk of P loss from pastures or no-tillage cropland, where the properties of the P source can be very influential in P transport. However, using WS-P (or similar tests) when the organic P sources are incorporated into soils would only be successful if we assume that, while the actual concentrations of soluble or easily desorbable P in different soil types that are amended with organic P sources will vary widely, the relative concentrations would be similar for a wide range of soils. Given this, we recommend a regional, comprehensive laboratory-scale evaluation of the approach described in this paper to estimate PSC
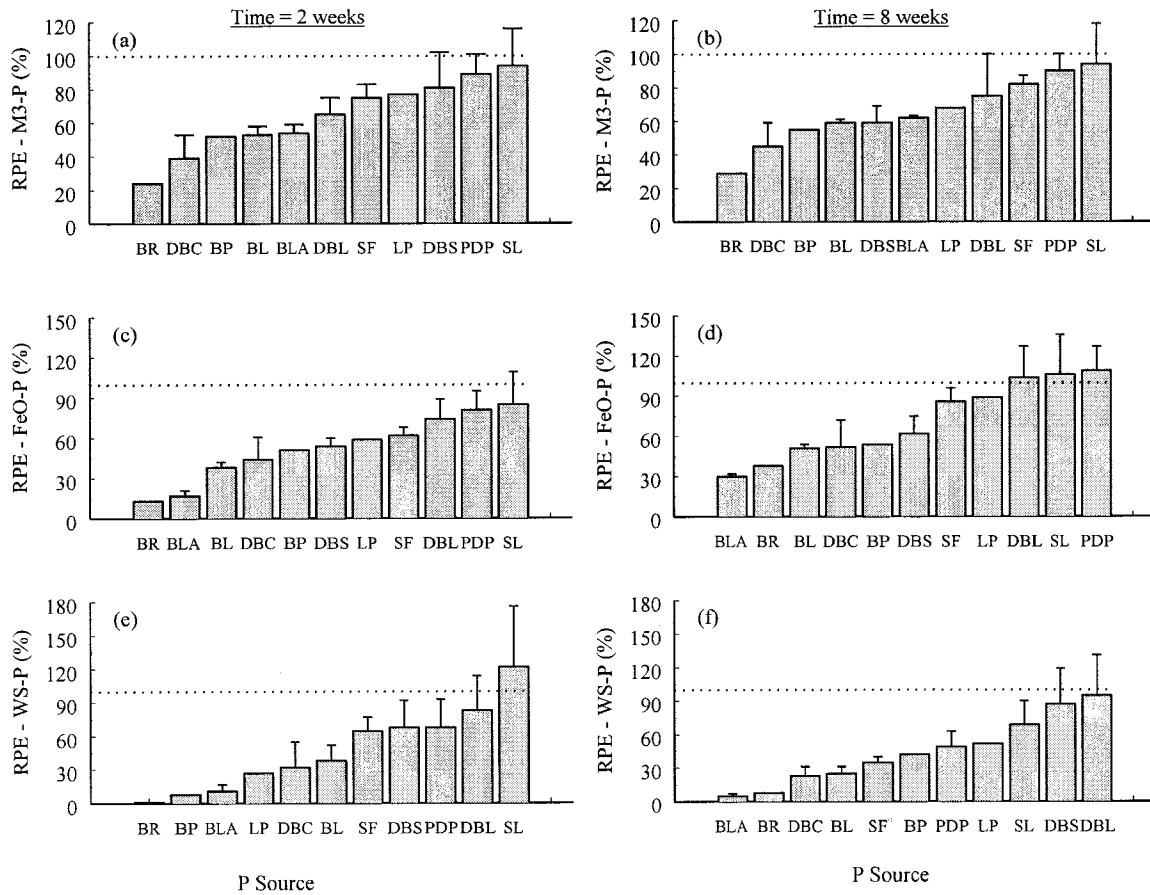
Fig. 4. Ranking, for each soil P test and sample date, of the relative P extractability (RPE) values for the 28 organic P sources. Bars in (a) to (f) are arranged in ascending order based on the RPE value for the soil P test and sample date. Dashed line in each graph represents the RPE value for the KH₂PO₄ source (100%). Error bars signify standard deviation of the means within source category. BL, broiler litter; BLA, broiler litter with alum; BP, Blue Plains; BR, Back River; LP, Little Patuxent; DBC, dairy/beef compost; DBL, dairy/beef liquid; DBS, dairy/beef solid; PDP, poultry—deep pit; SF, swine—fresh; SL, swine—liquid.
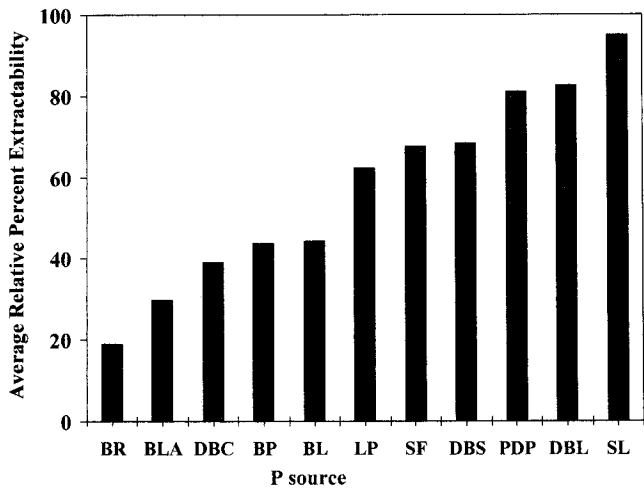

Fig. 5. Overall relative P extractability (RPE) ranking, based on the average value of all RPE for each soil test and sample date, for the 11 types of organic P sources evaluated in the incubation study. BL, broiler litter; BLA, broiler litter with alum; BP, Blue Plains; BR, Back River; LP, Little Patuxent; DBC, dairy/beef compost; DBL, dairy/beef liquid; DBS, dairy/beef solid; PDP, poultry—deep pit; SF, swine—fresh; SL, swine—liquid.
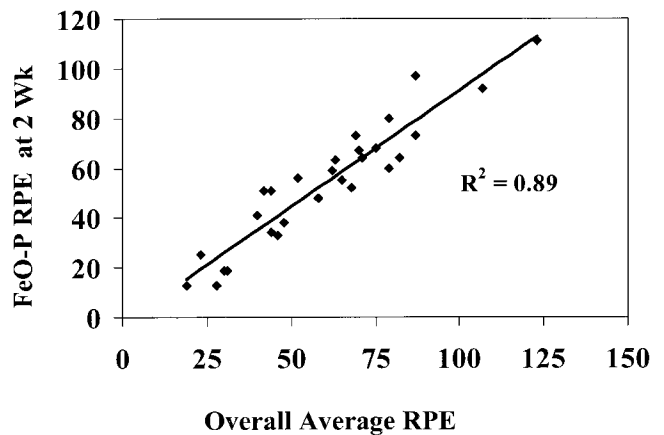

Fig. 6. Relationship between overall relative P extractability (RPE) ranking and iron-oxide strip extractable P (FeO-P) RPE ranking at 2 wk after treatment incorporation.

values for organic P sources. This approach should use a wide range of soils and organic P sources and would be analogous to regional efforts conducted to estimate N mineralization constants for animal manures, composts, and biosolids.

REFERENCES

Chardon, W.S., R.G. Menon, and S.H. Chien. 1996. Iron oxide impregnated filter paper (pi test): A review of its development and methodological research. Nutr. Cycling Agroecosyst. 46:41–51.

Codling, E.E., R.L. Chaney, and C.L. Mulchi. 2000. Use of aluminum- and iron-rich residues to immobilize phosphorus in poultry litter and litter-amended soils. J. Environ. Qual. 29:1924–1931.

Dao, T.H., L.J. Sikora, A. Hamasaki, and R.L. Chaney. 2001. Manure phosphorus extractability as affected by aluminum- and iron by-products and aerobic composting. J. Environ. Qual. 30:1693–1698.

Elliott, H.A., G.A. O'Connor, P. Lu, and S. Brinton. 2002. Influence of water treatment residuals on phosphorus solubility and leaching. J. Environ. Qual. 31:1362–1369.

Evanylo, G.K. 1999. Land application of biosolids for agricultural purposes in Virginia. Virginia Coop. Ext., Virginia Tech, Blacksburg.

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.

Maguire, R.O., J.T. Sims, S.K. Dentel, F.J. Coale, and J.T. Mah. 2001. Relationships between biosolids treatment process and soil phosphorus availability. J. Environ. Qual. 30:1023–1033.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409–1416.

Moore, P.A., Jr., T.C. Daniel, and D.R. Edwards. 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminum sulfate. J. Environ. Qual. 29:37–49.

Penn, C.J., and J.T. Sims. 2002. Phosphorus forms in biosolids-amended soils and losses in runoff: Effects of wastewater treatment process. J. Environ. Qual. 31:1349–1361.

Ritter, W.F. 1986. Water quality of agricultural coastal plain watersheds. Agric. Wastes 16:201–216.

Ritter, W.F. 1992. Delaware's Inland Bays: A case study. J. Environ. Sci. Health. (Part B) 27:63–68.

SAS Institute. 2002. Statistical analysis software, Version 8. SAS Inst., Cary, NC.

Sharpley, A., W. Gburek, and L. Heathwaite. 1998. Agricultural phosphorus and water quality: Sources, transport and management Agric. Food Sci. Finl. 7:297–314.

Sharpley, A.N., and B. Moyer. 2000. Phosphorus forms in manure and compost and their release during simulated rainfall. J. Environ. Qual. 19:1462–1469.

Siddique, M.T., J.S. Robinson, and B.J. Alloway. 2000. Phosphorus reactions and leaching potential in soils amended with sewage sludge. J. Environ. Qual. 29:1931–1938.

Sims, J.T., and F.J. Coale. 2002. Solutions to nutrient management problems in the Chesapeake Bay watershed, USA. p. 345–371. In P.M. Haygarth and S.C. Jarris (ed.) Agriculture, hydrology, and water quality. CAB International, Oxfordshire, UK.

Sims, J.T., and S.E. Heckendorn. 1991. Methods of analysis of the University of Delaware soil testing laboratory. Coop. Bull. no. 10. Univ. of Delaware, Newark.

Sims, J.T., R.O. Maguire, A.B. Leytem, K.L. Gartley, and M.C. Pautler. 2002. Evaluation of Mehlich 3 as an agri-environmental soil phosphorus test for the Mid-Atlantic United States. Soil Sci. Soc. Am. J. 66:2016–2032.

Sims, J.T., and N.J. Luka-McCafferty. 2002. On-farm evaluation of aluminum sulfate (alum) as a poultry litter amendment: Effects on litter properties. J. Environ. Qual. 31:2066–2073.

Stehouwer, R.C., A.M. Wolf, and W.T. Dotie. 2000. Chemical monitoring of sewage sludge in Pennsylvania: Variability and application uncertainty. J. Environ. Qual. 29:1686–1695.