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Availability of Residual Phosphorus in Manured Soils

Andrew N. Sharpley*

ABSTRACT

In many areas with confined animal operations, continual manure application has increased soil P above amounts sufficient for optimum crop yields. In these areas, it is of economic and environmental importance to determine how long high-P soils will remain above crop sufficiency and identify soils where P contents would decrease most rapidly under similar management conditions. Thus, the surface 5 cm of 23 high-P soils (85–419 mg kg^{-1} Mehlich-3 P) in Oklahoma and Texas, which had received beef feedlot, poultry, or swine manure (90–1880 kg P ha^{-1} yr^{-1} for up to 35 yr) were successively extracted with Fe-oxide-impregnated paper strips to investigate residual soil P availability. A decrease in strip P with successive extractions followed the equation: Strip P = a(extraction number)$^{-b}$ (r^2 of 0.88–0.98). The rate of P release to strips (exponent b) decreased more rapidly as soil P sorption saturation increased (R^2 of 0.79). Phosphorus saturation also accounted for 85% of the variation in the total amount of P released to strips from manured soils in 15 successive extractions (51–572 mg kg^{-1}). Fractionation of soil P before and after strip extraction showed bicarbonate inorganic P contributed most of the P released to strips (46%). The above equation also described soil P release in several published field studies (r^2 of 0.77–0.98). Thus, successive strip extraction of soil has the potential to describe soil factors controlling the availability of residual P and identify soils where high P contents may be less buffered and, thus, decrease more rapidly than others under similar management conditions.

The acceleration of freshwater eutrophication by increased inputs of P from agricultural runoff is of increasing concern in certain regions of the USA (U.S. Environmental Protection Agency, 1994). Much of this concern centers around the accumulation of P in surface soils receiving continual long-term applications of fertilizer and/or manures (Sharpley et al., 1994a). In many areas of intensive confined livestock production, manures are normally applied at rates designed to meet crop N requirements and avoid groundwater quality problems created by leaching of excess N. This often results in a buildup of soil P above amounts sufficient for optimal crop yields. For example, beef feedlot waste contributed to Bray-I P contents of 370 mg kg^{-1} in Texas (Sharpley et al., 1984), dairy manure to 200 mg kg^{-1} in Wisconsin (Motschall and Daniel, 1982), poultry litter to 280 mg kg^{-1} in Oklahoma (Sharpley et al., 1993), and swine slurry to 150 mg kg^{-1} in Oklahoma (Sharpley et al., 1991).

Once soil P exceeds amounts sufficient for optimum crop yields, how long will soil P remain excessive and will the P content of certain soils decrease more rapidly than others under similar management conditions, due to differing soil P sorption–desorption properties? These questions will be of concern to many farmers integrating fertilizer and manure into agronomically and environmentally sound management systems and targeting high-P soils for most effective remediation. For example, if a field has a high potential to enrich runoff and entrained sediment with P due to excessive soil P, how long will it be before manure can be applied without unacceptably increasing the potential for P loss? McCollum (1991) estimated that without further P, 16 to 18 yr of corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] production would be needed to deplete Mehlich-3 P in a Portsmouth fine sandy loam (fine-loamy over sandy or sandy-skeletal, mixed, thermic Typic Umbraquult) from 100 mg kg^{-1} to the agronomic threshold of 20 mg kg^{-1}. Similar rates of depletion with successive cropping have been observed for Olsen P (Halvorson and Black, 1985), Bray-I P (Hooker et al., 1983), and resin P (Wagar et al., 1986).

As soil depletion can take several decades, greenhouse studies have investigated the rate of soil P decrease (Adepoju et al., 1982; Novias and Kamprath, 1978). However, more rapid soil extraction methods are needed to assess the effect of P addition and soil type on the rate of decrease in available soil P. One promising approach is the use of Fe-oxide-impregnated paper strips (Fe-oxide strips) as a sink for P released from soil (Sharpley et al., 1994a). Acting as a sink for P, the Fe-oxide strips have a sounder theoretical basis than chemical extractants in estimating available soil P. Thus, the strip method may estimate plant-available P for a wide range of soil types (Sharpley et al., 1994b). Repeated extraction of a soil sample with Fe-oxide strips was evaluated as a method to investigate the release of soil P as a function of soil type, management, and fertility status and thereby assess residual P availability of high-P soils.

This study investigated the release of soil P during successive Fe-oxide strip extraction of 23 high-P soils (82–418 mg kg^{-1} Mehlich-3 P) from Oklahoma and Texas. These soils have received beef feedlot manure, poultry litter, or swine slurry (35–1880 kg P ha^{-1} yr^{-1}) for up to 35 yr and exhibit a wide range of physical and chemical properties.

MATERIALS AND METHODS

Soils

Soils receiving beef feedlot manure in the Texas Panhandle (Potter County), poultry litter in southeast Oklahoma (LeFlore and McCurtain counties), and swine manure in northeast Oklahoma (Delaware County) were selected (Table 1). The selected sites reflect typical agricultural soils of the area receiving manure and were all on gentle slopes (<2% slope) so that changes in properties due to erosion or deposition would be minimal. Beef feedlot manure was applied to irrigated grain sorghum [*Sorghum bicolor* (L.) Moench] prior to moldboard plowing about 20 cm deep in the spring. Manure was applied to all sites in 1968, after which each plot received manure at different rates and durations for 8 yr (Table 1). Soils treated with

USDA-ARS, Pasture Systems and Watershed Management Research Laboratory, Curtin Road, University Park, PA 16802-3702. Received 24 July 1995. *Corresponding author (ans3@psu.edu).

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Abbreviations: IP, inorganic phosphorus; OP, organic phosphorus.

Table 1. Site characteristics and selected properties of the surface 5 cm of treated soils.

Soil	Classification	Estimated manure applied†	Study duration	Estimated total P applied	Clay	pH	Organic C
		Mg ha^{-1} yr^{-1}	yr	kg ha^{-1}	%		g kg^{-1}
			Beef feedlot manure				
Pullman cl	Torrertic Paleustoll	0	8	0	30	7.1	8.5
		22(8)§	8	700	30	7.2	9.2
		67(8)	8	2150	30	7.2	14.1
		538(1)	8	2150	30	7.0	9.7
		134(5)	8	2700	30	7.2	11.4
		269(5)	8	5400	30	7.0	22.0
		538(3)	8	6450	30	6.9	14.3
			Poultry litter				
Cahaba vfsl‡	Typic Hapludult	9.0	12	1750	8	6.3	43.9
Captina sl	Typic Fragiudult	5.6	15	1350	19	6.3	55.0
Carnasaw fsl	Typic Hapludult	5.6	20	1800	15	6.1	60.0
Gallion fsl	Typic Hapludalf	7.8¶	12	750	6	5.9	19.4
Kullit fsl	Aquic Paleudult	9.0	12	1750	16	6.1	55.6
Muskogee l	Aquic Paleudalf	9.0	12	1750	10	7.3	59.6
Neff sil	Aquultic Hapludalf	4.5¶	35	1250	23	5.4	55.7
Rexor l	Ultic Hapludalf	6.7	12	1300	17	6.9	35.0
Rexor sil	Ultic Hapludalf	6.7	12	1300	21	5.6	49.0
Ruston fsl	Ultic Hapludalf	6.7	12	1300	6	6.1	33.7
Sallisaw l	Typic Paleudalf	4.5¶	35	1250	11	5.9	33.6
Shermore fsl	Typic Fragiudalf	5.6	20	1800	10	5.7	56.8
Stigler sl	Aquic Paleudalf	4.5¶	35	1250	19	5.8	33.4
			Swine slurry				
Captina sl	Typic Fragiudalf	22.1	9	350	11	5.9	22.6
Sallisaw sl	Typic Paleudalf	47.8	15	1200	13	5.4	18.2
Stigler sl	Aquic Paleudalf	61.1	9	950	32	5.8	22.7

† Poultry litter and beef feedlot manure applied on a dry-weight basis (Mg ha^{-1} yr^{-1}) and swine manure as a slurry (m^3 ha^{-1} yr^{-1}). Poultry litter and swine slurry applied every year unless noted otherwise.
‡ vfsl, fsl, sl, sil, l, and cl represent very fine sandy loam, fine sandy loam, sandy loam, silt loam, loam, and clay loam, respectively.
§ In parentheses is number of years manure applied, e.g., 67(8) = 67 Mg ha^{-1} yr^{-1} applied for 8 yr, 269(5) = 269 Mg ha^{-1} yr^{-1} applied for the first 5 yr, and 538(1) = 538 Mg ha^{-1} yr^{-1} applied the first year with none the subsequent seven.
¶ Litter applied every other year.

poultry litter and swine manure were cropped with 'Coastal' or 'Midland' bermudagrass [*Cynodon dactylon* (L.) Pers.] cut for hay approximately twice a year. No mineral fertilizer N or P was applied during the period of manure application. Information on the rate and duration of manure application at each site was obtained from the landowner. For poultry litter, pine shavings were used as bedding material in the broiler houses.

The same soil types on adjacent areas that had not received manure (untreated) were also sampled for baseline information. The sampled areas adjacent to those receiving beef feedlot manure were under irrigated unfertilized grain sorghum. Untreated soils similar to those receiving poultry litter and swine manure were all under idle unfertilized native grass. Native grasses were big (*Andropogen geradii* Vitman) and little [*Schizachyrium scoparium* (Michaux.) Nash] bluestem, tall dropseed [*Sporobolus drummondii* (trin) Vasey-Fernald], and side-oats grama [*Bouteloua cutipendula* (Michaux.) Torrey].

At each site, treated and untreated soils were sampled on the same day by taking six 2.5-cm-diam. cores to a 5-cm depth. The beef feedlot sites were sampled in April 1976, poultry litter sites in July 1990, and swine slurry sites in June 1989. Soil cores were air dried, composited, and sieved (2 mm). The samples were stored in airtight containers for later analysis. Manure samples were collected on the day of application for the year when soils were sampled. Beef feedlot manure and poultry litter samples were air dried, lightly ground for subsampling uniformity, and kept at 277 K until P analysis. Swine slurry samples were kept moist at 277 K until analyzed.

Analyses

Soil clay content was determined by pipette analysis after dispersion with sodium hexametaphosphate (Day, 1965), organic C by dichromate wet combustion (Raveh and Avnimelech, 1972), and pH using a glass electrode at a 5:1 water/soil ratio (w/w). The total P content of soil and manure was determined following digestion with a semimicro-Kjeldahl procedure (Bremner and Mulvaney, 1982).

The Mehlich-3 P content of soil was determined by extraction of 1 g of soil with 10 mL of extractant (Mehlich, 1984). The strip P content of soil was determined using Fe-oxide strips (Sharpley, 1993). One strip was shaken with 1 g of soil in 40 mL of 0.01 *M* $CaCl_2$ for 16 h end-over-end at 298 K. The strip was then removed, rinsed free of soil particles, and shaken end-over-end for 1 h in 40 mL of 1 *M* HCl to remove sorbed P subsequently referred to as "strip P". Phosphorus in all neutralized extracts was determined by the colorimetric method of Murphy and Riley (1962).

Phosphorus sorption isotherms were constructed using the procedure of Nair et al. (1984). One gram of soil was shaken with various additions of P (0–500 mg kg^{-1} added as KH_2PO_4) in 25 mL of 0.01 *M* $CaCl_2$ on an end-over-end shaker at 298 K. After 24 h, the soil suspensions were centrifuged and filtered (0.45 μm) and the solution P concentration (C) determined. The amount of P sorbed (X) is the difference between P added and P remaining in solution. Using the Langmuir sorption equation, soil P sorption maximum was calculated as the reciprocal of the slope of the plot C/X vs. C (Syers et al., 1973). The sorption saturation of each soil was calculated as the percentage of soil P sorption maximum as strip P (i.e., P saturation = [strip P/P sorption maximum of untreated soil] × 100; Breeuwsma and Silva, 1992).

Sequential Extractions

One gram of treated soil was shaken with 40 mL of 0.01 *M* $CaCl_2$ and an Fe-oxide strip for 16 h end-over-end at 298 K. The strip was then removed after slow up-and-down

Table 2. Phosphorus properties of soils untreated (Untr.) and treated (Tr.) with manure.†

Soil	Mehlich 3 P		Strip P		Total P		P sorption max.		P saturation‡	
	Untr.	Tr.	Untr.	Tr.	Untr.	Tr.	Untr.	Tr.	Untr.	Tr.
	mg kg^{-1}								%	
					Beef feedlot manure					
Pullman 0	19	19	12		353		582		2.1	
22(8)§	19	85	12	32	353	538	582	292	2.1	5.5
67(8)	19	257	12	92	353	996	582	208	2.1	15.8
538(1)	19	165	12	57	353	553	582	316	2.1	9.8
134(5)	19	203	12	79	353	696	582	262	2.1	13.6
269(5)	19	418	12	147	353	1278	582	146	2.1	25.3
538(3)	19	286	12	93	353	824	582	270	2.1	16.0
					Poultry litter					
Cahaba	9	259	6	76	169	626	556	278	1.1	13.7
Captina	5	338	3	115	273	1103	915	148	0.3	12.6
Carnasaw	7	277	7	72	404	2384	1126	690	0.6	6.4
Gallion	32	190	13	62	350	533	286	299	4.5	21.7
Kullit	6	207	4	63	122	1430	680	358	0.6	9.3
Muskogee	6	356	7	76	570	1308	1200	482	0.6	6.3
Neff	7	119	8	39	559	1362	980	554	0.8	4.0
Rexor l	11	188	12	74	470	785	896	474	1.3	8.3
Rexor sil	15	145	11	46	410	713	279	461	3.9	16.5
Ruston	16	409	12	125	240	1015	502	262	2.4	24.9
Sallisaw	8	152	4	57	226	1178	488	294	0.8	11.7
Shermore	6	205	5	72	206	1554	736	244	0.7	9.9
Stigler	17	229	9	78	381	1577	416	243	2.2	18.8
					Swine slurry					
Captina	5	121	3	58	273	566	834	92	0.4	7.0
Sallisaw	6	147	8	63	226	436	451	154	1.8	14.0
Stigler	15	82	16	33	116	336	576	214	2.8	5.7

† For all P properties, treated soils were significantly different from untreated soils at $P < 0.01$, as determined by analysis of variance for paired data.
‡ P sorption saturation calculated as (strip P/P sorption maximum of untreated soil) × 100.
§ In parentheses is number of years manure applied, e.g., 67(8) = 67 Mg ha^{-1} yr^{-1} applied for 8 yr, 269(5) = 269 Mg ha^{-1} yr^{-1} applied for the first 5 yr, and 538(1) = 538 Mg ha^{-1} yr^{-1} applied the first year with none the subsequent seven.

movement of the strip in the supernatant to remove adhering soil particles. A fresh strip was placed in the suspension and shaken for another 16 h. This strip removal and replacement was repeated to give a total of 15 sequential extractions. After these extractions, the soil–0.01 *M* $CaCl_2$ suspension was centrifuged (266 m s^{-1} for 5 min) and supernatant decanted. The volume of supernatant remaining after decantation was determined by difference in weight before and after drying, to calculate solution P carryover to the P fractionation procedure. The remaining soil was air dried to determine the loss of soil during sequential strip extraction.

Soil IP and OP before and after the sequential strip extraction was fractionated according to the procedure of Hedley et al. (1982). This involved sequential extraction of 0.5 g of soil with 30 mL each of 0.5 *M* $NaHCO_3$ (pH 8.5), 0.1 *M* NaOH, and 1.0 *M* HCl for 16 h. The residual soil was finally digested with 18 *M* H_2SO_4 and 70% H_2O_2. Total P in the bicarbonate and hydroxide extracts was determined following perchloric acid digestion (Olsen and Sommers, 1982). Phosphorus in all filtered and neutralized extracts and digests was determined by the molybdenum-blue method of Murphy and Riley (1962). The OP content of bicarbonate and hydroxide extracts was calculated as the difference between total P and IP contents. Fractions are subsequently referred to as bicarbonate IP (biologically available IP), hydroxide IP (amorphous and some crystalline Al and Fe phosphates), acid IP (relatively stable Ca-bound P), bicarbonate OP (easily mineralizable OP), hydroxide OP (chemically and physically protected organic forms), and stable P (a resistant mixture of occluded IP covered with sesquioxides, Ca-bound IP included in other minerals, and nonextracted stable OP) (Hedley et al., 1982).

All analyses were conducted in duplicate and mean values are presented. Statistical differences among treatment effects and their significance were evaluated by analysis of variance for paired data.

RESULTS AND DISCUSSION

The total P concentration of manure collected from the landowners prior to application averaged 4 g kg^{-1} for beef feedlot manure, 16 g kg^{-1} for poultry litter, and 1.7 g L^{-1} for swine slurry (dry-weight basis). The P concentration of manure will vary with type of feed, number and length of exposure of animals to bedding material, and dilution by cleaning water and soil material. Manure application rates as stated by landowners may also vary from year to year. Even so, manure P concentrations enable estimation of amounts of P added to treated soils.

The loss of soil during sequential extraction averaged 0.04 ± 0.023 g or 4% of the 1 g initially used. Thus, loss of soil during the 15 extractions was negligible, and changes in strip P are a function of soil P rather than loss of soil. Furthermore, the carryover of P to the sequential P fractionation in the supernatant remaining in the final strip extraction (about 0.5 mL) was minimal, averaging 0.12 mg kg^{-1}.

Manure application increased soil P concentration and P saturation ($P < 0.01$), but decreased P sorption maxima of the surface 5 cm of each soil (Table 2). Mehlich-3 P was about three times greater than strip P for all treated soils (Table 2). Strip P ranged from 32 to 147 mg kg^{-1} (82–418 mg kg^{-1} Mehlich-3 P), while a sevenfold variation in P sorption maxima was obtained (92–690 mg kg^{-1}). This resulted in a wide range of P sorption saturation of treated soils (4.0–25.3%; Table 2). Thus, the soils studied exhibit a wide range in residual P and sorption properties for the study of P release characteristics. A detailed discussion of the effects of manure application on P forms and sorptivity in these soils was given by Sharpley et al. (1984, 1993).

Rate of Phosphorus Released

The release of strip P decreased rapidly with successive extractions (Fig. 1). The soils used to obtain the results in Fig. 1 range widely in initial strip P (Table 2). The other soils showed a similar rapid decrease in release of strip P, with an average 65% of the total P released in 15 extractions occurring in the first five extractions for all 23 soils.

The release of strip P with successive extractions is described by an exponential-type relationship, as represented by the data given in Fig. 1 (R^2 of 0.88–0.98; $P < 0.001$; Table 3):

$$\text{Strip P} = a(\text{extraction number})^{-b} \qquad [1]$$

Constant a of this relationship represents strip P obtained with a single extraction (Table 3). In fact, constant a was closely related (r^2 of 0.94; $P < 0.001$) to initial strip P concentration of the treated soils, with a regression slope of 1.1. Constant b of the relationship describing successive strip P release (Eq. [1]) represents the rate of P release per strip extraction of soil (Table 3). An increase in constant b indicates a decrease in the rate of P release with successive extraction of soil. For Pullman soil treated with beef feedlot manure, b ranged from −0.682 to −1.091 (Table 3) and was a linear function of the initial strip P concentration of treated soils (r^2 of 0.86; $P < 0.05$). As strip P concentration of manured Pullman soil increased, the rate of P release from this pool increased. However, b for the 16 soil types treated with poultry and swine manure was not related to initial strip P (r^2 of 0.06). Apparently, the relationship between the rate of strip P release and pool size is soil specific.

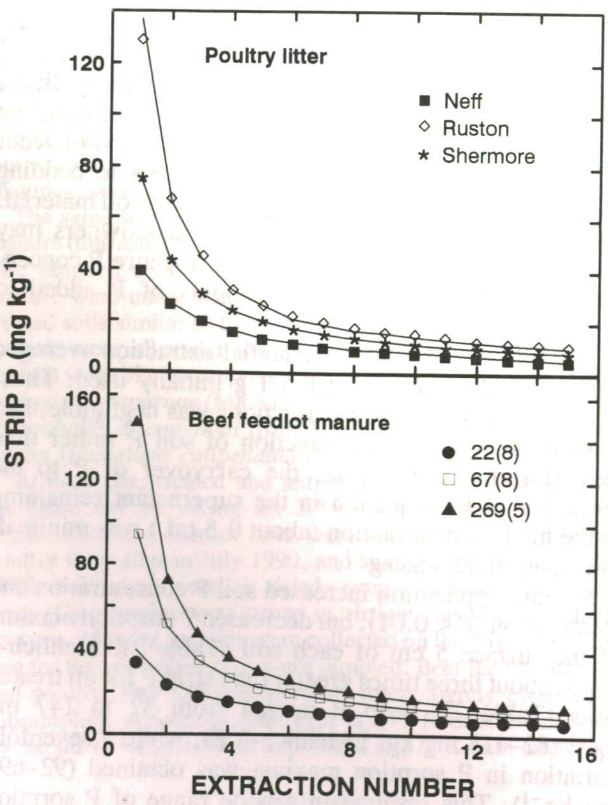

Fig. 1. Strip P released from soils treated with poultry litter and beef feedlot manure during successive extractions.

The value of constant b for soils treated with poultry and swine manure ranged from −0.391 to −1.050 (Table 3) as a function of P sorption maxima of corresponding untreated soil (Fig. 2). Phosphorus sorption maxima described 76% of the variability in the rate of decrease in P release with successive extractions. Thus, the rate of decrease in P released as measured by strips varied with the amount of P added as well as soil type. Soils receiving beef feedlot manure did not vary in P sorption maxima, which precluded this soil property from having any effect on the rate of decrease in P release (constant b, Fig. 2).

Constant b for all soils and manure treatments was related ($P < 0.01$) to P sorption saturation, calculated as the percentage of untreated soil P sorption maxima as initial strip P (i.e., P saturation = [initial strip P/Langmuir P sorption maximum] × 100; Fig. 3). Phosphorus sorption saturation described 79% of the variability in constant b due to differences in both soil type and manure P added. This may be attributed to the fact that P saturation accounts for the capacity of different soils

Table 3. Total strip P released during 15 extractions, final strip P after the extractions, and slope, intercept, and correlation coefficient for the regression of strip P and number of successive extractions.

Soil	Total strip P released	Final strip P	P release–extraction regression†		
			a	b	R^2
	——— mg kg⁻¹ ———				
		Beef feedlot manure			
Pullman 0	85	3.6	9	−0.698	0.96
22(8)‡	51	6.1	39	−0.682	0.96
67(8)	372	10.9	95	−0.908	0.98
538(1)	86	9.1	54	−0.913	0.98
134(5)	167	9.5	66	−0.965	0.98
269(5)	537	12.4	155	−1.091	0.98
538(3)	211	13.1	88	−0.999	0.96
		Poultry litter			
Cahaba	187	10.3	65	−0.903	0.98
Captina	304	8.5	126	−0.868	0.98
Carnasaw	544	8.5	66	−0.567	0.98
Gallion	111	7.9	72	−1.010	0.92
Kullit	395	8.7	46	−0.892	0.94
Muskogee	198	7.4	80	−0.391	0.98
Neff	147	4.9	40	−0.516	0.98
Rexor l	105	7.0	78	−0.856	0.98
Rexor sil	145	6.2	35	−1.027	0.88
Ruston	542	10.0	137	−1.050	0.96
Sallisaw	270	6.8	60	−0.844	0.96
Shermore	446	8.1	76	−0.827	0.96
Stigler	572	9.4	68	−0.988	0.94
		Swine slurry			
Captina	106	3.7	47	−0.732	0.98
Sallisaw	95	5.9	57	−1.015	0.98
Stigler	62	6.8	27	−0.805	0.98

† All relationships significant at $P < 0.001$.

‡ In parentheses is number of years manure applied, e.g., 67(8) = 67 Mg ha⁻¹ yr⁻¹ applied for 8 yr, 269(5) = 269 Mg ha⁻¹ yr⁻¹ applied for the first 5 yr, and 538(1) = 538 Mg ha⁻¹ yr⁻¹ applied the first year with none the subsequent seven.

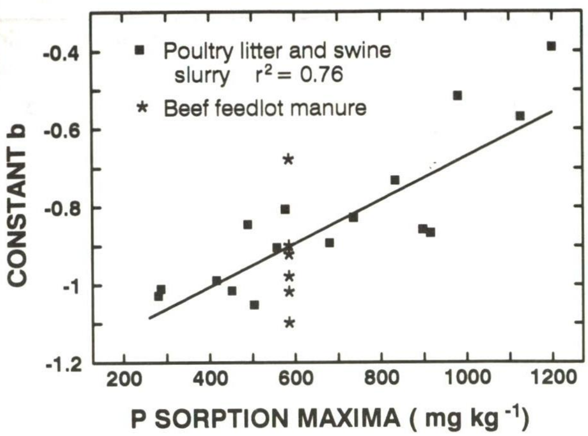

Fig. 2. Relationship between constant b of the strip P successive extraction regression for manured soils and P sorption maximum of corresponding untreated soils.

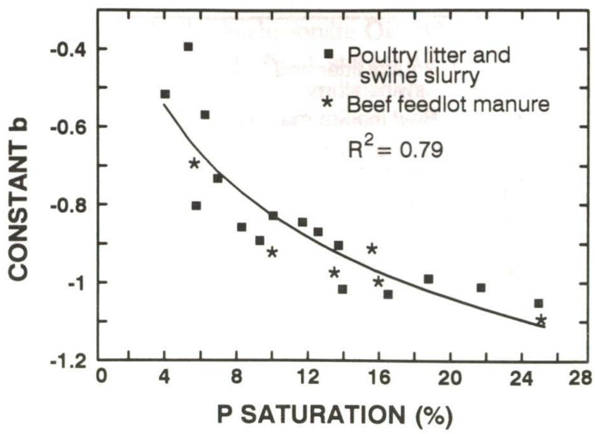

Fig. 3. Relationship between constant b of the strip P successive extraction regression and P sorption saturation of manured soils.

to sorb P and the degree to which these sites have been satisfied by P added in manure. The release of P from a range of soil types to surface runoff (Sharpley, 1995) and drainage water (Breeuwsma and Silva, 1992) has also been found to be related to P saturation.

Several studies have shown a decline in soil test P (Bray-I, Mehlich-1, or Olsen P) over a number of years with repeated cropping where no P was added (Table 4). Equation [1] described extractable soil P decrease in these studies when the number of years of P decrease since the last P application was substituted for extraction number in the equation (Table 4). The range in constant b for the field studies (-0.190 to -1.225) was greater than observed in the laboratory extraction of this study (-0.391 to -1.091; Table 3). Even so, successive strip P extractions may provide a representation of chemical processes controlling soil P release in the field.

Amounts of Phosphorus Released

The total amount of strip P released during 15 successive extractions ranged from 51 to 572 mg kg^{-1} (Table 3). The release of strip P was not closely related to the initial strip P concentration of treated soil (r^2 of 0.40; $P > 0.05$). For example, Cahaba, Rexor loam, Shermore, and Stigler soils treated with poultry litter had similar initial strip P concentrations (76, 74, 72, and 78 mg kg^{-1}, respectively), but released a total of 187, 105, 446, and 572 mg kg^{-1} of strip P, respectively, after 15 extractions (Table 3). However, as a percentage of total P increase with manure application (i.e., the difference

Table 4. Constant b of Eq. [1] fitted to the decrease in extractable soil P with time for several field studies.

Soil	Location	Crop	Time	Soil P Method	Soil P Amount	b	R^2	Reference
			yr		mg kg^{-1}			
Thurlow, loam	MT	Small grains	9	Olsen	13	−0.594	0.96	Campbell, 1965
			9		20	−0.846	0.94	
			9		60	−1.098	0.92	
Georgeville, silty clay loam	NC	Small grains	7	Mehlich 1	7	−0.234	0.88	Cox et al., 1981
			7		16	−0.538	0.85	
Haverhill, clay loam	Sask.	Wheat-fallow	14	Olsen	90	−0.190	0.86	
			14		165	−0.304	0.88	
			14		300	−0.369	0.94	
Portsmouth, fine sandy loam	NC	Small grains	8	Mehlich 1	51	−0.348	0.94	
			9		122	−0.332	0.83	
Sceptre, clay	Sask.	Wheat-fallow	8	Olsen	100	−0.498	0.77	
			8		150	−0.613	0.85	
			8		330	−0.641	0.94	
Williams, loam	MT	Wheat-barley	16	Olsen	26	−0.448	0.86	Halverson and Black, 1985
			16		45	−0.495	0.85	
Richfield, silty clay loam	KS	Corn	8	Bray I	12	−0.194	0.98	Hooker et al., 1983
					22	−0.221	0.96	
Carroll, clay loam	Manitoba	Wheat-flax	8	Olsen	71	−1.225	0.96	Spratt et al., 1980
			8		135	−1.187	0.88	
			8		222	−0.931	0.90	
Waskada, loam	Manitoba	Wheat-flax	8	Olsen	48	−1.099	0.86	
			8		88	−0.846	0.90	
			8		200	−0.908	0.85	
Waskada, clay loam	Manitoba	Wheat-flax	8	Resin	140	−0.550	0.94	Wagar et al., 1986
			8		320	−0.714	0.98	

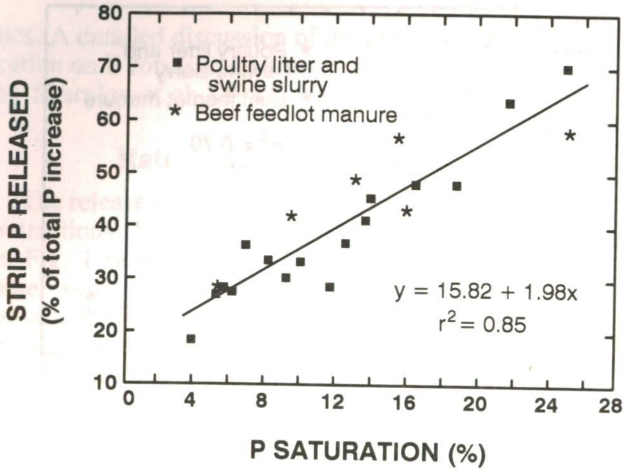

Fig. 4. Relationship between the percentage total P increase with manure application, released as strip P during 15 successive extractions and P sorption saturation.

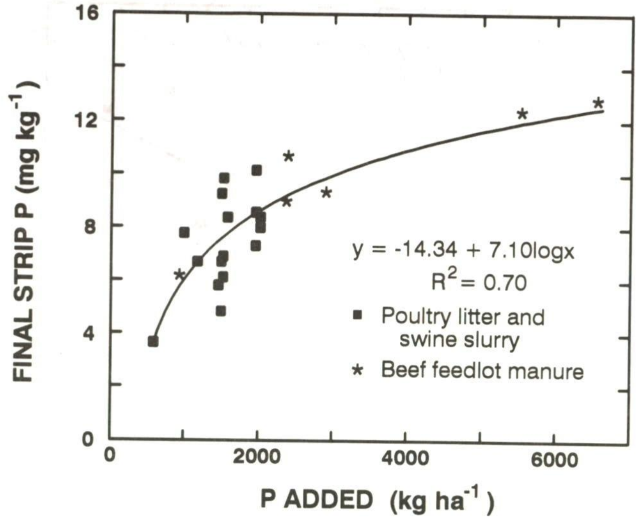

Fig. 5. Relationship between final strip P after 15 successive extractions of treated soils and amount of P added in manure.

between the total P concentration of treated and untreated soil), strip P released was related ($P < 0.01$) to P sorption saturation of treated soils (Fig. 4). Phosphorus saturation accounted for 85% of the variation in the amount of strip P released as a percentage of total P increase in soils treated with beef feedlot, poultry, and swine manure. Thus, both the rate and amount of P release from manured soils is a function of P saturation.

The strip P content of treated soil after 15 successive extractions (final strip P) varied with soil type (Table 3) but was not related to the initial strip P concentration of untreated soil (r^2 of 0.03; $P > 0.05$). For example, the final strip P concentration of Pullman soil treated with beef feedlot manure ranged from 6.1 to 13.1 mg kg^{-1}, although untreated Pullman soil had 12 mg kg^{-1} strip P. However, final strip P was related ($P < 0.05$) to the amount of P added as manure to each soil (Fig. 5). When regressions were performed using both P saturation and the amount of manure P added as independent vari-

Table 5. The distribution of P forms in soils treated with manure before and after 15 successive strip extractions.

	Total P		Inorganic P						Organic P				Stable P	
			Bicarbonate		Hydroxide		Acid		Bicarbonate		Hydroxide			
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
	— mg kg⁻¹ —													
							Beef feedlot manure							
22(8)†	538	472	63	38	121	109	110	92	58	52	103	100	83	81
67(8)	996	608	149	6	219	146	289	183	100	61	169	148	70	64
538(1)	553	440	73	28	143	120	117	88	34	26	98	94	88	84
134(5)	696	519	96	17	163	131	188	148	56	42	102	94	91	87
269(5)	1278	733	214	9	308	196	332	185	96	55	212	183	116	105
538(3)	824	600	140	26	177	144	206	158	51	38	149	143	101	91
							Poulty/litter							
Cahaba	625	417	114	12	89	53	236	191	34	22	72	66	80	73
Captina	1103	785	206	47	275	223	217	144	38	21	219	209	148	141
Carnasaw	2439	1895	257	17	1028	927	321	217	142	97	228	205	463	432
Gallion	533	408	88	25	171	149	76	48	11	5	50	47	137	134
Kullit	1411	1007	237	28	227	155	346	259	185	167	167	158	249	240
Muskogee	1298	1083	203	98	296	262	223	172	124	111	214	208	238	232
Neff	794	646	66	9	129	99	74	36	32	20	248	242	245	240
Rexor	696	571	136	71	118	98	94	72	60	51	148	143	140	136
Rexor sl	713	552	132	47	218	193	84	55	26	13	139	134	114	110
Ruston	1091	545	289	12	177	79	303	200	60	20	63	46	199	188
Sallisaw	1178	908	87	7	361	292	218	144	54	32	157	143	301	290
Shermore	1350	904	191	5	432	333	144	36	124	98	194	177	265	255
Stigler	1487	915	235	6	314	188	259	111	106	76	215	193	358	341
							Swine slurry							
Captina	567	446	97	31	129	109	119	97	21	15	39	36	162	158
Sallisaw	486	386	96	39	80	68	89	73	26	18	60	55	135	133
Stigler	526	452	80	46	127	116	71	55	20	14	93	88	135	133
Average‡	963a	695b	148a	28b	241a	190b	187a	129b	66a	48b	143a	132b	178a	170b

† In parentheses is number of years manure applied, e.g., 67(8) = 67 Mg ha^{-1} yr^{-1} applied for 8 yr, 269(5) = 269 Mg ha^{-1} yr^{-1} applied for the first 5 yr, and 538(1) = 538 Mg ha^{-1} yr^{-1} applied the first year with none the subsequent seven.
‡ Averages followed by different letters are significantly different ($P < 0.05$) as determined by analysis of variance for paired data.

ables, the variation explained in final strip P increased from 70 to 81%.

For Pullman soil, the final strip P concentration of soils treated with beef feedlot manure (6.1–13.1 mg kg^{-1}) was greater than that for untreated soil (3.6 mg kg^{-1}; Table 3). As strip P concentration of manured soils decreases with successive extraction or cropping, a new equilibrium concentration of available P is established, which is greater than for untreated soils. Thus, application of manure appears to affect the long-term release of P from soil. Similar effects have been found after fertilizer P application. For example, Halvorson and Black (1985) observed that 16 yr after P was added (45, 90, or 180 kg P ha^{-1}) to a Williams loam (fine-loamy, mixed Typic Argiboroll) in Montana, Olsen P remained greater (8, 9, or 14 mg kg^{-1}, respectively) than in unfertilized soil (5 mg kg^{-1}).

Forms of Phosphorus Released

Soil P was sequentially fractionated before and after the 15 successive extractions to determine the forms of P released as strip P (Table 5). Significant decreases in each IP and OP fraction ($P < 0.05$) were observed following successive strip P extractions (Table 6). Bicarbonate IP accounted for the greatest proportion of strip P released during the 15 extractions, ranging from 29 to 57% (mean = 46%; Fig. 6). Hydroxide and acid IP contributed similar proportions of P to strip P released (about 20%); as did bicarbonate OP, hydroxide OP, and stable P (<10%; Fig. 6). Clearly, IP fractions (86%) contributed more P to strip P release than did OP fractions (11%). Manure type had no effect on the relative contribution of P fractions to strip P released.

Table 6. Change in each P fraction as a percentage of total P decrease during successive strip extraction of soils treated with manure.

	Inorganic P			Organic P		Residual P
	Bicarbonate	Hydroxide	Acid	Bicarbonate	Hydroxide	
	%					
			Beef feedlot manure			
22(8)†	25	19	26	11	12	8
67(8)	34	17	25	9	12	1
538(1)	21	21	24	8	15	11
134(5)	23	21	26	9	12	9
269(5)	30	19	26	9	9	6
538(3)	28	22	25	7	12	6
			Poultry litter			
Cahaba	29	20	27	7	9	8
Captina	31	20	23	4	11	11
Carnasaw	43	18	19	8	4	7
Gallion	31	22	23	2	10	11
Kullit	64	9	7	5	6	8
Muskogee	28	23	26	8	8	7
Neff	37	21	16	3	15	7
Rexor	44	17	21	6	6	6
Rexor sl	48	27	10	3	7	5
Ruston	49	15	16	6	7	6
Sallisaw	29	20	25	8	10	8
Shermore	49	15	15	7	5	8
Stigler	51	16	15	7	5	6
			Swine slurry			
Captina	37	19	23	5	8	8
Sallisaw	44	18	21	4	6	7
Stigler	52	15	11	5	6	11
Average	38	19	21	6	9	8

† In parentheses is number of years manure applied, e.g., 67(8) = 67 Mg ha^{-1} yr^{-1} applied for 8 yr, 269(5) = 269 Mg ha^{-1} yr^{-1} applied for the first 5 yr, and 538(1) = 538 Mg ha^{-1} yr^{-1} applied the first year with none the subsequent seven.

The relative contributions of P fractions to strip P decrease (Fig. 6) are similar to those found by Wagar et al. (1986) for a Waskada clay loam in a wheat–flax rotation in Manitoba. Resin (76%) and bicarbonate IP (11%) contributed the major proportion of total P decrease (289 mg kg^{-1}) 8 yr after application of 400 kg fertilizer P ha^{-1} (Wagar et al., 1986). Smaller contributions were made from hydroxide IP (8%), acid IP (2%), bicarbonate OP (1%), and hydroxide OP (5%), while stable P increased (3%).

It is likely that as P is released from bicarbonate IP and hydrolyzed from bicarbonate OP pools, a general shift in P from hydroxide to bicarbonate pools occurs. Also, dissolution of acid-extractable Ca-bound IP, accumulated during manure application, occurs. The movement of P from resistant to more available or easily extracted forms of soil P is controlled by the decrease in bicarbonate IP. A similar shift of soil P to plant-available forms was observed for several grassed and cropped fertilized soils (Sharpley, 1985).

The rate of movement between these fractions will also be a function of soil moisture, temperature, complexation/precipitation reactions, and probably pool sizes. It is likely that no distinct boundaries exist between the IP and OP fractions. Also, movement of P between fractions occurs simultaneously. However, the fractionation scheme used does allow some distinctions to be made as to the relative importance of IP and OP fractions in supplying residual strip P release.

CONCLUSIONS

The use of Fe-oxide strips and Eq. [1] to investigate the availability of residual P in high-P soils has important

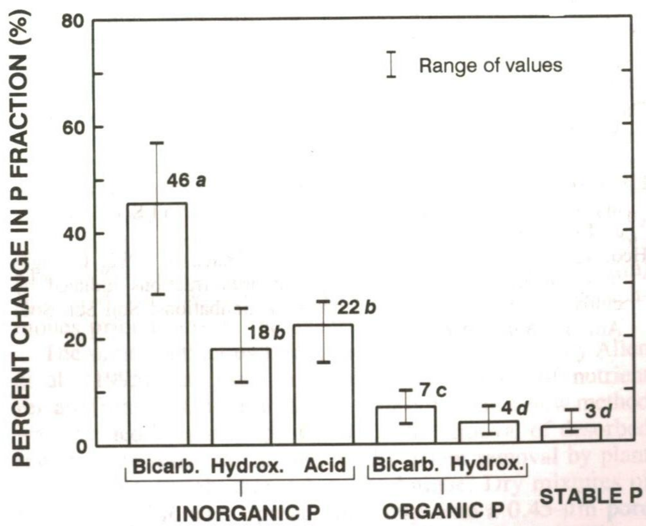

Fig. 6. The decrease in each P fraction as a percentage of strip P released during successive strip extractions of treated soil (number above bar is mean; means followed by different letters are significantly different at $P < 0.05$).

agronomic and environmental implications to fertilizer and particularly manure P management. For example, Carnasaw and Shermore soils treated with poultry litter had the same strip P concentration (72 mg kg^{-1}; Table 2) and different P sorption saturations (6.4 and 9.9%, respectively). Using Eq. [1], Carnasaw would decrease to a strip P concentration of 20 mg kg^{-1} in nine extractions, while Shermore would decline to the same value in only four extractions. This suggests that under similar agronomic conditions, the release of soil P for crop uptake and removal will be more rapid from Shermore than from Carnasaw.

The results of this study show that Fe-oxide strips can be used to describe the rate of P release from high-P soils due to manure applications. The rate of soil P release decreases rapidly followed by a more gradual decline. Differences in residual P, total amount of P released, and minimum strip P among soils is accounted for by soil P sorption saturation and amount of P added in manure. Equation [1] described the release of P from 23 soils in this laboratory extraction and the annual decline in extractable soil P following P application in several field studies. Also, values of the rate constant (b) for strip P decrease in Eq. [1] were similar for both this and field studies. Thus, the successive Fe-oxide-strip extraction of high-P soils may provide a realistic representation of soil P release under field conditions.

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