Soil Mixing to Decrease Surface Stratification of Phosphorus in Manured Soils

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ABSTRACT

Continual applications of fertilizer and manure to permanent grassland or no-till soils can lead to an accumulation of P at the surface, which in turn increases the potential for P loss in overland flow. To investigate the feasibility of redistributing surface stratified P within the soil profile by plowing, Mehlich-3 P rich surface soils (128–961 mg kg^{-1} in 0–5 cm) were incubated with lower-P subsoil (16–119 mg kg^{-1} in 5–20 cm) for 18 manured soils from Oklahoma and Pennsylvania that had received long-term manure applications (60–150 kg P ha^{-1} yr^{-1} as dairy, poultry, or swine manure for up to 20 yr). After incubating a mixture of 5 g surface soil (0- to 5-cm depth) and 15 g subsoil (5- to 20-cm depth) for 28 d, Mehlich-3 P decreased 66 to 90% as a function of the weighted mean Mehlich-3 P of surface and subsoil (i.e., 1:3 ratio) ($r^2 = 0.87$). At Klingerstown, Northumberland County, south central Pennsylvania, a P-stratified Berks soil (Typic Dystrochrept) (495 mg kg^{-1} Mehlich-3 P in 0- to 5-cm depth) was chisel plowed to about 25 cm and orchardgrass (*Dactylis glomerata* L.) planted. Once grass was established and erosion minimized (about 20 wk after plowing and planting), total P concentration in overland flow during a 30-min rainfall (6.5 cm h^{-1}) was 1.79 mg L^{-1} compared with 3.4 mg L^{-1} before plowing, with dissolved P reduced from 2.9 to 0.3 mg L^{-1}. Plowing P-stratified soils has the potential to decrease P loss in overland flow, as long as plowing-induced erosion is minimized.

THE CONTINUAL BROADCAST APPLICATION of P in fertilizer and manure without incorporation can accumulate P and lower P sorption at the surface compared with deeper layers in the soil (Kingery et al., 1994; Sharpley et al., 1993; Sims et al., 1998). This has been shown to increase the potential for P loss in overland flow, especially as dissolved P from pastures and no-till soils (Pierson et al., 2001; Pote et al., 1999; Sharpley and Smith, 1994). However, the draw down of high soil P by crop removal is slow, with McCollum (1991) estimating that after ceasing P applications, 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 (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-1 P (Hooker et al., 1983), and resin P (Wagar et al., 1986). The decline in soil test P concentrations of surface soils under pasture is expected to be even slower, due to the lower rates of P uptake and harvest offtake from the field (Pierson et al., 2001; Sharpley, 1999a). Clearly, farmers need some immediate or short-term practices that can decrease soil P stratification and the enrichment of overland flow with P.

One approach to decreasing soil P stratification is tillage that will redistribute and mix high-P surface soil with low-P subsoil. Several studies have reported a decrease in surface soil P (as Bray-1, Olsen, and total P in 0 to 5- or 10-cm depths) and redistribution of P within the soil profile after plowing P-stratified soils (Morrison and Chichester, 1994; Pezzarossa et al., 1995; Rehm et al., 1995). For four fertilized soils (20–78 kg ha^{-1} yr^{-1} for 12 yr), Weil et al. (1988) found that dilute acid extractable P in the 0- to 4-cm depth was about three times lower under tilled (16–54 mg kg^{-1}) than no-till corn (28–233 mg kg^{-1}). Tilled soils were moldboard plowed to a 15- to 20-cm depth in spring.

The above decreases in surface soil–extractable P result from the combined processes of dilution and sorption when high P surface soil (approximately 0–5 cm) was mixed with a large amount of subsoil (approximately 5–30 cm) with a lower P concentration and higher P sorption capacity and binding energy (Guertal et al., 1991; Sharpley, 1999b). For instance Weill et al. (1990) found moldboard plowing of no-till corn decreased Bray-1 P in the 0- to 5-cm depth from 156 to 100 kg P ha^{-1} for a clay soil, with no significant change in a sandy loam soil (178 and 186 kg ha^{-1}).

Phosphorus sorption following mixing has been found to be an important process in overland and stream flow systems, where the input of P-deficient or high P sorbing subsoil can resorb dissolved P in overland and stream flow (McDowell et al., 2001, 2002; Sharpley et al., 1981). In fact, Kunishi et al. (1972) found dissolved P concentrations of about 0.2 mg L^{-1} in overland flow from fertilized fields were decreased to <0.1 mg L^{-1} as it moved 10 km downstream in the Mahantango Creek watershed, Pennsylvania. This was attributed to sorption of P by subsoil and stream bank material during movement downstream (Taylor and Kunishi, 1971).

The objective of this study was to determine the effect of plowing on the concentration and forms of P in soils highly stratified with respect to P, as a result of continual, long-term application of manure. This was evaluated by laboratory incubation of high-P surface soil and low-P subsoil in differing ratios for 10 Oklahoma and 8 Pennsylvania soils, which had a large accumulation of P in the surface 5 cm, due to continual manure (dairy, poultry, and swine) application. In addition, the loss of P in overland flow from a P-stratified Berks channery silt loam soil (Typic Dystrochrept) before and after moldboard plowing (15- to 25-cm depth) was measured under field and simulated rainfall conditions.

MATERIALS AND METHODS

Site Management and Soil Collection

The classification, location, and management history of the selected sites and soils are presented in Table 1. Sampled soils are located in LeFlore and McCurtain counties of eastern Oklahoma and Lancaster and Northumberland counties of

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Table 1. Site location and management of the soils used in this study.

Soil†	Classification	Management	Manure application: Type	Rate	Duration‡
				kg P ha^{-1} yr^{-1}	yr
			LeFlore County, OK		
Carnasaw, fsl	Typic Hapludult	Coastal bermudagrass	Poultry litter	85	20
Rexor, sil	Ultic Hapludalf	Coastal bermudagrass	Poultry litter	100	12
Sallisaw, l	Typic Paleudalf	Coastal bermudagrass	Poultry litter	85	20
Shermore, fsl	Typic Fragiudalf	Coastal bermudagrass	Poultry litter	85	20
Stigler, sl	Aquic Paleudalf	Coastal bermudagrass	Poultry litter	90	20
			McCurtain County, OK		
Cahaba, vfsl	Typic Hapludult	Coastal bermudagrass§	Poultry litter	130	12
Captina, sil	Typic Fragiudult	Fescue pasture¶	Swine manure	100	9
Gallion, fsl	Typic Hapludalf	Coastal bermudagrass	Poultry litter	60	12
Kullit, fsl	Aquic Paleudult	Coastal bermudagrass	Poultry litter	130	12
Ruston, fsl	Typic Paleudult	Coastal bermudagrass	Poultry litter	100	12
			Lancaster County, PA		
Bucks, sil	Ultic Hapludalf	Reduced till corn–barley	Poultry manure	120	10
Chester, sil	Typic Hapludalf	Reduced till corn–soybean	Dairy manure	120	10
Duffield, sil	Typic Hapludalf	Pasture	Dairy manure	120	10
Hagerstown, sil	Ultic Hapludalf	Reduced till corn–soybean	Poultry manure	180	10
			Northumberland County, PA		
Berks, l	Typic Dystrochrept	No till corn–soybean	Poultry manure	150	8
Calvin, l	Typic Dystrochrept	No till corn–soybean	Swine slurry	100	10
Hartleton, l	Typic Hapludult	No till corn–soybean	Swine slurry	100	10
Watson, cl	Typic Fragiudult	No till corn–soybean	Swine slurry	85	8

† vfsl, fsl, sl, sil, l, and cl represent very fine sandy loam, fine sandy loam, sandy loam, silt loam, loam, and clay loam texture, respectively, for the surface 5 cm of the soil profile.

‡ Approximate minimum number of years manure applied.

§ Cut for hay.

¶ Fescue pasture was intermittently cut and grazed for hay.

central and southeastern Pennsylvania and all are typical of areas in these regions with concentrated animal feeding operations. Annual rainfall in eastern Oklahoma is about 1200 mm and in central and southeastern Pennsylvania about 1100 mm. All sites are on gently sloping areas (<2% slope), so any changes in soil properties due to erosion would be minimal. Information on the rate and duration of manure application at each site was obtained from landowners, with no mineral fertilizer applied at least 10 yr before soil sampling.

Eighteen soil profiles with high surface soil P were selected from Oklahoma (10 sites) and Pennsylvania (eight sites). At each site, soils were sampled by taking six 5-cm diameter cores to a depth of 100 cm. The six cores for each incremental soil profile depth were composited. Samples were air-dried and sieved (2 mm) to give a sample for 0- to 5-, 5- to 10-, 10- to 15-, 15- to 20-, 20- to 25-, 25- to 30-, 30- to 50-, 50- to 75-, and 75- to 100-cm depths for each soil profile. The samples were stored in air-tight containers for later analysis.

Soil Mixing and Incubation

Samples of 0- to 5-cm and composited 5- to 20-cm depths were mixed in ratios of 20:0, 15:5, 10:10, 5:15, and 0:20 (gram wt. basis) to simulate varying degrees of soil mixing by plowing. Soil mixtures were moistened to field capacity (approximately 30% soil water capacity), covered to prevent dust contamination, and regularly rewetted to prevent drying during incubation for 28 d at 298 K. After incubation, soil mixtures were air-dried and Mehlich-3 extractable P, P sorption, and P sorption saturation of each mixture was determined by methods described below.

Overland Flow Studies

Site Selection and Treatment

The transport of P and sediment in overland flow before and after plowing a high-P soil was evaluated using simulated rainfall. The soil was located in the mixed land-use watershed, FD-36 (Northumberland County, south central Pennsylvania); a 39.5-ha subwatershed in the Mahantango Creek, which discharges into the Susquehanna River and ultimately the Chesapeake Bay.

In late March 2000, three overland flow plots described below, were set up in FD-36 on the high-P Berks loam (495 mg P kg^{-1} in the 0- to 5-cm depth) that was in no-till corn and received poultry manure for the last 8 yr (Table 1). Two simulated rainfalls, each of 6.5 cm h^{-1} for 30 min of runoff, were applied on consecutive days and overland flow volume, P concentration (dissolved, particulate, and total P), and sediment discharge measured, as described below. Rainfall and overland flow collection was repeated 1, 3, and 6 wk later. Metal plates delineating the overland flow plots were then removed and the field chisel plowed to a depth of about 25 cm, disked to prepare seedbed surface, and orchardgrass planted in mid-May 2000. Overland flow plots were then returned to the same landscape location with a survey transect and kept in place for the remainder of the study. Rainfall and overland flow collection, as described above, was then conducted 1, 2, 4, 8, 16, 20, 44, and 52 wk after plowing.

Three overland flow plots were installed on a high P Berks loam (411 mg kg^{-1}) in no-till corn that was not plowed. In addition, three plots were set up in a low P Berks loam (25 mg kg^{-1}) under orchardgrass in a field adjacent to the high P soil. Simulated rainfall was applied to the unplowed low P plots on the same day as the plowed high P Berks plots, but during the same period on the unplowed high P Berks plots. The low P plots were not plowed and served as a control, with plot borders remaining in place throughout the study. Data presented in this paper represent the average of flow-weighted concentrations for each of the two events and three plots for both plowed and unplowed soil.

Soils were sampled before and after plowing by taking six 5-cm diameter cores to a depth of 100 cm, air-dried, compos-

Table 2. Selected physical and chemical properties of the 0- to 5- and 5- to 20-cm depths of soils used in this study.

	pH		Clay		Organic C		Total P	
Soil	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–5 cm	5–20 cm
			%		$g\ kg^{-1}$		$mg\ kg^{-1}$	
Berks	7.1	6.8	37	31	16.6	3.2	1034	218
Bucks	7.1	6.8	15	25	17.3	4.8	1861	226
Cahaba	6.3	6.5	18	44	43.9	4.1	626	189
Calvin	5.8	6.0	31	46	9.0	2.2	958	237
Captina	5.9	6.3	11	22	22.6	3.5	703	163
Carnasaw	6.1	5.8	15	16	60.0	4.2	2384	356
Chester	6.3	6.4	23	16	19.4	6.5	2138	256
Duffield	6.9	6.6	18	23	16.2	5.1	1958	308
Gallion	5.9	6.0	6	9	19.4	4.6	533	159
Hagerstown	6.7	6.5	22	40	22.4	7.3	734	180
Hartleton	5.7	6.1	26	48	16.5	6.1	893	274
Kullit	6.1	5.7	16	24	55.6	2.2	1430	299
Rexor	6.9	7.1	17	31	35.0	11.5	713	326
Ruston	6.1	6.2	12	19	33.7	6.9	1015	317
Sallisaw	5.9	5.8	21	31	33.6	8.7	1178	472
Shermore	5.7	5.9	10	48	56.8	3.3	1554	291
Stigler	5.6	5.9	17	36	32.2	3.7	1577	312
Watson	6.8	6.6	35	46	15.2	1.9	920	416

ited in depth increments as described earlier, sieved (2 mm), and stored for analysis.

Overland Flow Plots and Rainfall Simulation

Overland flow plots, each 1 by 2 m, with the long axis orientated down the slope, were delineated by metal borders installed 5 cm above and below ground level to isolate overland flow. The slope of all plots was between 4 and 5%. Rainfall was applied to each plot with one TeeJet 2HH-SS50WSQ[1] nozzle approximately 2.5 m above the soil to achieve terminal velocity (Sharpley et al., 2002). The nozzle, associated plumbing, in-line filter, pressure gauge, and electrical wiring are mounted on a 3 by 3 by 3 m aluminum frame, fitted with canvas walls to provide a windscreen. A coefficient of uniformity of 85% was obtained for rainfall over a 2-m^2 footprint, which encompasses one pair of abutting plots. A rainfall intensity of 6.5 cm h^{-1} was applied to the plots until 30 min of runoff was obtained. This rainfall intensity and duration has an approximate 10-yr return frequency in south central Pennsylvania. Local ground water was used as the water source for the simulator, and had a dissolved reactive P concentration of <0.01 mg L^{-1}, total P of <0.02 mg L^{-1}, nitrate-N of 3.1 mg L^{-1}, and pH of 5.7.

Overland flow was collected in metal gutters at the downslope edge of each plot and pumped to 200-L (50-gallon) plastic containers. Total overland flow was measured by weighing the containers. A runoff sample was collected from each container after thorough mixing and agitation, and a subsample was immediately filtered (0.45 μm) and stored at 277 K. Filtered samples were analyzed within 24 h of collection and unfiltered samples no more than 7 d after the completion of the rainfall simulation. All methods used in plot design and installation, rainfall simulation and runoff collection, and analysis, follow protocols detailed in the National Phosphorus Research Project (National Phosphorus Research Project, 2002).

Chemical Analyses

Soil Samples

All analyses were conducted on air-dried and sieved (2 mm) samples. Soil sand, silt, and clay contents were determined by hydrometer after dispersion with sodium hexametaphosphate (Gee and Bauder, 1986). Organic C was determined by combustion using a Leco C/N analyzer and pH using a glass electrode at a 1:2.5 soil/water ratio (w/w). Values of these properties for the 0- to 5- and 5- to 20-cm depths are given in Table 2.

Mehlich-3 extractable soil P concentration was determined by shaking 1 g soil with 10 mL of 0.2 *M* CH_3 COOH, 0.25 *M* NH_4NO_3, 0.015 *M* NH_4F, 0.013 *M* HNO_3, and 0.001 *M* EDTA end-over-end for 5 min (Mehlich, 1984). Total soil P was determined following digestion with a semi–micro-Kjeldahl procedure (Bremner and Mulvaney, 1982) (Table 2).

Phosphorus sorption isotherms were constructed using the procedure of Nair et al. (1984). One gram of the soil mixture 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 and binding energy as slope/intercept of the same plot (Syers et al., 1973). The sorption saturation of each soil was calculated as the percentage of soil P sorption maximum as Mehlich-3 extractable P (Kleinman and Sharpley, 2002) as below:

$$\text{Soil P sorption saturation} = \frac{\text{Mehlich-3 soil P}}{\text{P sorption maximum} + \text{Mehlich-3 soil P}} \times 100 \quad [1]$$

Phosphorus in all filtrates and neutralized extracts and digests was measured by the colorimetric method of Murphy and Riley (1962).

Water Samples

The concentration of dissolved reactive P (subsequently referred to as *dissolved P*) in overland flow was determined for 0.45 μm filtered sample. The concentration of both total dissolved and total P was determined on filtered and unfiltered runoff samples, respectively, following digestion with a semi–micro-Kjeldahl procedure (Bremner and Mulvaney, 1982). Phosphorus in all filtrates and neutralized digests was measured by the colorimetric method of Murphy and Riley (1962). Particulate P was calculated as the difference between total P and total dissolved P. The suspended sediment concentration

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

Table 3. The Mehlich-3 extractable soil P, P sorption maxima, binding energy, and P sorption saturation of 0 to 5 cm, 5 to 20 cm, and mixed samples (5 g of 0- to 5-cm and 15 g of 5- to 20-cm depths incubated for 28 d) for the P-stratified soils studied.

Soil	Mehlich-3 P				P sorption maximum				Binding energy				P sorption saturation			
	0–5 cm	5–20 cm	Mix†	Decrease‡	0–5 cm	5–20 cm	Mix	Increase	0–5 cm	5–20 cm	Mix	Increase	0–5 cm	5–20 cm	Mix	Decrease
	mg kg^{-1}			%	mg kg^{-1}			%	L kg^{-1}				%			
Berks	495	60	85	83	263	843	641	59	0.08	0.26	0.18	125	65	2.3	7	90
Bucks	961	119	178	81	208	605	502	59	0.05	1.54	1.12	2140	82	3.0	26	68
Cahaba	292	22	35	88	142	703	474	70	0.03	2.57	1.12	3633	67	0.3	7	90
Calvin	394	38	58	85	250	843	628	60	0.07	0.71	0.52	643	61	4.3	8	86
Captina	172	24	42	76	196	542	450	56	0.13	3.84	2.45	1785	47	2.5	9	82
Carnisaw	259	30	56	78	229	599	540	58	0.15	1.19	0.92	513	53	1.6	9	82
Chester	911	118	272	70	183	304	274	33	0.04	0.88	0.65	1525	83	5.6	50	40
Duffield	706	102	201	72	224	477	412	46	0.08	0.54	0.29	263	76	11.0	33	57
Gallion	238	53	80	66	108	191	152	29	0.13	1.03	0.77	492	69	21.7	34	50
Hagerstown	343	23	35	90	477	815	677	30	0.05	2.67	1.21	2320	42	0.2	5	88
Hartleton	405	32	58	86	185	951	684	73	0.08	0.69	0.47	488	69	3.3	8	89
Kullit	128	18	28	78	315	465	395	20	0.22	3.16	2.60	1082	19	0.4	4	76
Rexor	143	16	28	80	280	506	425	34	0.01	1.29	0.50	4900	34	1.2	6	82
Ruston	386	43	95	75	106	343	204	48	0.10	1.41	1.10	1000	78	1.2	27	66
Sallisaw	220	22	37	83	341	772	549	38	0.09	4.32	1.83	1933	39	1.5	6	84
Shermore	240	21	33	86	254	698	502	49	0.02	2.87	2.01	9950	49	0.1	6	87
Stigler	366	49	76	79	123	580	411	70	0.05	0.92	0.63	1160	75	7.8	16	79
Watson	346	36	43	88	134	635	313	57	0.08	0.58	0.48	500	72	0.9	12	83
Avg.§	389a	46b	80c	80	223a	604b	457c	49	0.08a	1.69b	1.05c	1914	60a	3.8b	15c	77

† Soil value when 0- to 5-cm and 5- to 20-cm samples are mixed in a ratio of 1:3.

‡ Decrease or increase in mixture property as a percent of the 0- to 5-cm depth value.

§ For a given property, averages followed by different letters are significantly different ($P > 0.01$) as determined by analysis of variance for paired data.

of each overland flow event was measured in duplicate as the difference in weight of 250 mL aliquots of unfiltered and filtered (0.45 μm) runoff samples after evaporation (378 K) to dryness.

Statistical Analysis

All soil incubations, extractions, and sorption isotherms were conducted in duplicate, with means presented in this paper. In all cases, standard deviations were <2.5% of the mean value. Results of the overland flow studies are presented as means of triplicate treatments, with standard deviations of individual data <5% of mean values. Statistical analyses (*t* tests, means, and standard errors) were performed with SPSS v10.0 (SPSS, 1999). All r^2 values given are significant at the $P < 0.05$ level.

RESULTS AND DISCUSSION

Soil Profile Phosphorus Characteristics

Surface soil Mehlich-3 extractable P (0- to 5-cm depth) in the 18 sampled profiles was well above optimum fescue response levels in Oklahoma (65 mg kg^{-1}; Zhang et al., 2002) and crop response levels in Pennsylvania (30–60 mg kg^{-1}; Beegle, 2001) (Table 3). This is due to the continued N-based application of manure, supplying appreciably more P than crop removal (Tables 1 and 3). Although Mehlich-3 P concentration ranged from 128 to 961 mg kg^{-1} in surface samples, levels declined rapidly with depth, as exampled by Berks, Duffield, Hagerstown, and Watson soils in Fig. 1. Similar profile trends were obtained for the other soils, which are not shown. In fact, compared with a composited 5- to 20-cm depth sample, surface soil Mehlich-3 P concentrations were 10 to 20 times greater ($P < 0.01$; Table 3).

The P sorption properties of the surface 5 cm of soil were also affected by the long-term application of manure (Table 3). Phosphorus sorption maxima were 2 to 4.5 times lower ($P < 0.01$) in the surface 5 cm of soil (avg. 223 mg kg^{-1}) than 5- to 20-cm composite samples (avg. 604 mg kg^{-1}). Similarly, P binding energy was significantly lower ($P < 0.01$) in the 0- to 5-cm (0.08 L

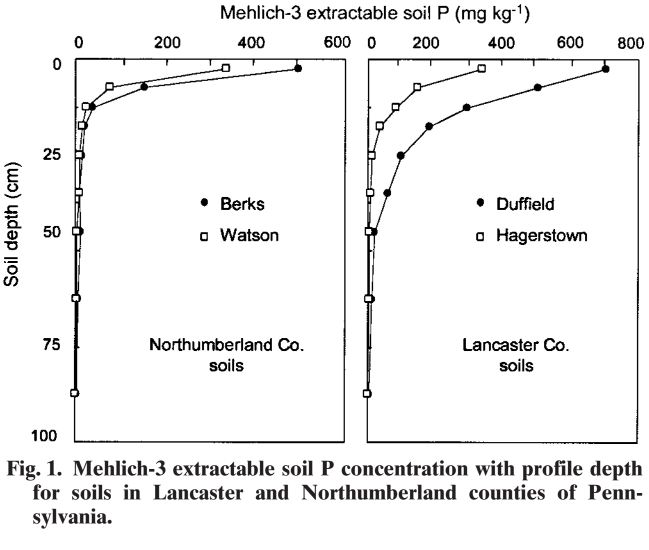

Fig. 1. Mehlich-3 extractable soil P concentration with profile depth for soils in Lancaster and Northumberland counties of Pennsylvania.

kg^{-1}) than 5- to 20-cm depth of soil (1.69 L kg^{-1}; Table 3). As a consequence, P sorption saturation was greater in the 0- to 5-cm (60%) than 5- to 20-cm depth (4%) (Table 3). Clearly, there is a greater propensity for P sorption at a greater energy of binding in subsoil (5–20 cm) than surface soil (0–5 cm) of these P-stratified manured soils. Guertal et al. (1991) also found an appreciably lower P sorption maximum in the surface 0- to 2-cm (25 mg kg^{-1}) than in the 16- to 18-cm depth (100 mg kg^{-1}) of an annually fertilized silty clay loam under no-till corn in Ohio.

Because of the pronounced surface stratification of Mehlich-3 P concentration and P sorption properties in manured soils, it is possible that mixing surface and subsoil material by profile inversion or plowing, may dilute and/or sorb P from high P surface layers. Thus, surface 5 cm and composite 5- to 20-cm soil samples were mixed and incubated in varying proportions to assess the potential for plowing to minimize soil P stratification and overland flow P enrichment.

Sample Mixing and Soil Phosphorus

Results for mixing soil from 0- to 5- and 5- to 20-cm depths in a 1:3 ratio are discussed in more detail than other combinations, as this ratio attempts to simulate the degree of horizon mixing during plowing to an approximate depth of 20 cm.

Mehlich–3 Extractable Soil Phosphorus

Mixing 0- to 5- and 5- to 20-cm samples decreased Mehlich-3 soil P compared with surface soil concentrations (Fig. 2). As expected, this decrease was greater with an increase in the proportion of subsoil mixed with surface soil. Similar trends were obtained with the other soils, which are not shown. There was an average decrease in surface soil Mehlich-3 P of 309 mg kg^{-1} (80% decline) when P-rich surface (0–5 cm) and low-P subsoil were mixed in a 1:3 ratio (Table 3).

In contrast to the wide range in surface soil Mehlich-3 P (128–961 mg kg^{-1}), the decline in surface Mehlich-3 P of a 1:3 mix was consistently >65% (66–90%; Table 3). This was the case, even though there was a wide range in subsoil Mehlich-3 P (16–119 mg kg^{-1}), P sorption maxima of surface soil (106–477 mg kg^{-1}), and subsoil (191–951 mg kg^{-1}), and binding energy of P in surface soil (0.01–0.22 L kg^{-1}) and subsoil (0.26–4.32 L kg^{-1}). For example, surface soil Mehlich-3 P concentrations of Gallion (238 mg kg^{-1}) and Shermore (240 mg kg^{-1}) soils were similar, but declined a respective 66 and 86% after mixing (Table 3). Conversely, the Mehlich-3 P concentration of Carnisaw and Kullit soils declined 78% after mixing, while having respective Mehlich-3 concentrations of 259 and 128 mg kg^{-1}.

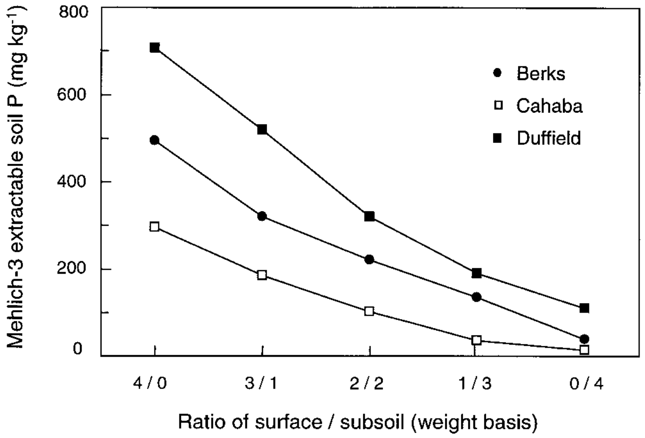

Fig. 2. Mehlich-3 extractable soil P concentration as a function of mixing 0- to 5- and 5- to 20-cm depth samples in ratios of 4:0, 3:1, 2:2, 1:3, and 0:4.

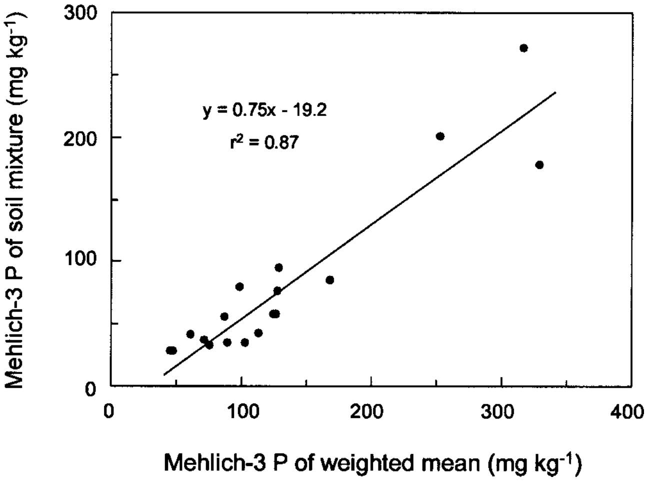

Fig. 3. The Mehlich-3 extractable soil P of a mixture of 5 g of 0- to 5-cm and 15 g of 5- to 20-cm depth samples (i.e., 1:3 ratio) as a function of the weighted mean of Mehlich-3 P of 0- to 5-cm and 15 g of 5- to 20-cm depth samples for the 18 Oklahoma and Pennsylvania profiles.

The Mehlich-3 P concentration of surface and subsoil mixture (1:3 ratio) was related to the weighted mean of premixed surface and subsoils (r^2 = 0.87; Fig. 3). The weighted mean of these two depth samples was calculated as:

$$(\text{Mehlich-3 P of 0 to 5 cm soil} + 3 \times \text{Mehlich-3 P of 5 to 20 cm soil})/4 \qquad [2]$$

Thus, the Mehlich-3 P of 0- to 5- and 5- to 20-cm depths can be used to indicate the potential benefit of plowing a P-stratified soil to decrease surface soil Mehlich-3 P. The slope of the relationship between the Mehlich-3 P of mixed and weighted mean of 0- to 5- and 5- to 20-cm depth samples (0.75; Fig. 3) also indicated that about 25% of surface soil Mehlich-3 P is sorbed by subsoil during mixing. The magnitude of resorption is consistent with that found by del Campillo et al. (1996) for water-extractable soil P of mixed soil samples (23–30% sorbed). The mechanism of sorption of P released from P-enriched surface soil by subsoil during mixing is supported by the fact that there was a greater decline in mixed soil Mehlich-3 P as P sorption maximum of subsoil increased (r^2 = 0.73; Fig. 4).

The decrease in Mehlich-3 extractable soil P with mixing surface and subsoil in varying proportions sug-

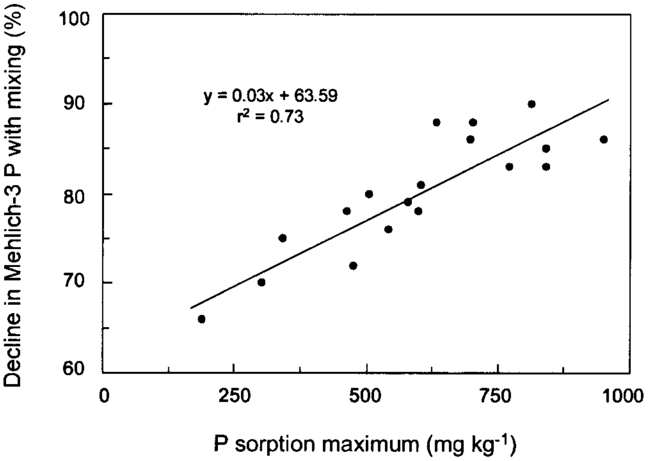

Fig. 4. The decline in Mehlich-3 extractable soil P of a mixture of 5 g of 0- to 5-cm and 15 g of 5- to 20-cm depth samples (i.e., 1:3 ratio) compared with 0- to 5-cm samples as a function of P sorption maximum of soil from the 5- to 20-cm depth for the 18 Oklahoma and Pennsylvania profiles.

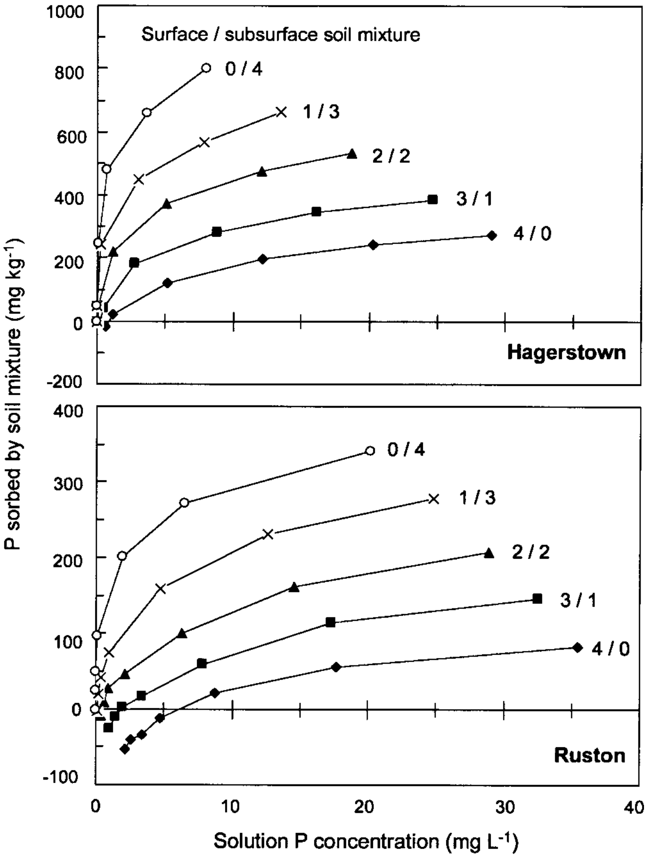

Fig. 5. Phosphorus sorption as a function of solution P concentration for 0- to 5- and 5- to 20-cm depth samples of soil mixed in ratios of 4:0, 3:1, 2:2, 1:3, and 0:4.

gests plowing may decrease the capacity of a soil to release P to overland flow. For instance, Oloya and Logan (1980) measured the *readily desorbable P* concentration (0.01M $CaCl_2$ extractable) of a no-till and fall-plowed Hoytville soil (fine, illitic, mesic Mollic Epiaqualfs) under soybean, each receiving 246 kg P ha^{-1} over 4 yr. Readily desorbable P was much lower in the plowed (1.6 mg kg^{-1}) than unplowed, no-till soil (15.6 mg kg^{-1}) (Oloya and Logan, 1980).

Phosphorus Sorption Properties

Phosphorus sorption consistently increased with an increase in the proportion of subsoil mixed with surface soil (Fig. 5). All soils exhibited the same effect of soil–mixture composition on P sorption isotherms, as shown by Hagerstown soil (fine, mixed, semiactive, mesic Typic Hapludalfs) and Ruston soil (fine-loamy, siliceous, semiactive, thermic Typic Paleudults) in Fig. 5. The effects of surface-subsoil mixing (1:3 ratio) was reflected in significantly greater ($P < 0.01$) P sorption maxima (avg. 457 mg kg^{-1}) and binding energy of sorption (1.05 L kg^{-1}) than of surface soil (223 mg kg^{-1} and 0.08 L kg^{-1}, respectively; Table 3). Averaged across all soils, there was a 49% increase in P sorption maximum and 1914% increase in binding energy relative to P-stratified surface soil, after mixing to approximate plowing. As a result of the changes in Mehlich-3 P and P sorption with mixing, the P sorption saturation of mixed surface and subsoil (avg. 15%) was significantly lower than surface soil (avg. 60%) ($P < 0.01$; Table 3).

The increase in P sorption maximum and binding energy of P with soil, as well as a decrease in P sorption saturation with surface and subsoil mixing, indicates plowing may increase P retention by soil, thereby decreasing the potential for soil P release to overland flow.

Plowing and Overland Flow Phosphorus

The dissolved P concentration of overland flow from the high P Berks soil averaged 2.9 mg L^{-1} for three rainfalls in 8 wk before plowing. During these flow events, particulate P averaged 0.5 mg L^{-1} and total P averaged 3.4 mg L^{-1}. Overland flow P from the no till plots was mostly dissolved P (85%). The concentration of P from the high P soil was appreciably greater ($P <$ 0.01) than from the low P plots, which averaged 0.02, 0.07, and 0.09 mg L^{-1} as dissolved, particulate, and total P, respectively (Fig. 6). Overland flow volume and sediment concentration were not significantly different ($P >$ 0.05) from high and low P Berks plots (Table 4).

Surface soil (0- to 5-cm depth) Mehlich-3 P concentration of the high P Berks soil used in the overland flow study was 495 mg kg^{-1} before plowing and 136 mg kg^{-1} immediately after plowing. The surface stratification of P found in this soil (Fig. 1) was decreased by plowing. In fact, Mehlich-3 P concentrations of 136, 95, 75, 84, and 42 mg kg^{-1} were measured in the 0- to 5-, 5- to 10-, 10- to 15-, 15- to 20-, and 20- to 30-cm depths in the plowed soil profile. Similarly, Oloya and Logan (1980) found a fall-plowed Hoytville soil had a uniform distribution of Bray-1 P in 0- to 5- and 5- to 15-cm depths (46.6 and 59.3 mg kg^{-1}, respectively), while the no-till analog was P stratified (183.9 and 29.3 mg kg^{-1}, respectively).

There was no change in dissolved P concentration of the first rainfall–overland flow event after plowing (2.86 mg L^{-1}) compared with before plowing (2.90 mg

Table 4. The overland flow volume, and sediment and P loss before (8 wk) and after plowing (52 wk) a high-P Berks soil (495 mg kg^{-1} Mehlich-3 P) and unplowed low-P (25 mg kg^{-1} Mehlich-3 P) and high-P Berks soil (411 mg kg^{-1} Mehlich-3 P).

Time	Overland flow	Sediment	Dissolved P	Particulate P	Total P	Enrichment ratio
weeks	L	kg ha^{-1}		g ha^{-1}		
			Unplowed low P Berks			
0	29	29	4	9	12	1.40
3	25	40	2	12	13	1.35
8	28	22	3	7	10	1.52
9	26	29	3	11	14	1.73
10	25	21	3	7	11	1.59
12	30	30	4	10	14	1.54
16	29	19	5	8	13	1.94
24	24	14	3	7	10	2.29
28	31	28	2	10	13	1.66
52	28	29	4	11	14	1.66
60	26	29	3	11	14	1.73
			Unplowed high P Berks			
5	26	26	325	39	325	2.48
10	28	28	378	70	448	3
20	32	48	448	64	512	2.1
30	25	50	288	63	351	1.97
50	27	14	324	27	351	3.55
			High P Berks			
0	26	25	364	68	432	2.93
3	28	22	448	63	511	3.01
8	31	34	419	84	502	2.63
			Plowed			
9	17	559	243	543	786	2.12
10	15	318	184	478	662	3.28
12	19	336	205	328	533	2.13
16	24	190	118	274	391	3.15
24	22	74	30	167	197	4.95
28	33	53	15	153	168	6.35
52	26	16	14	30	44	5.35
60	29	20	10	41	51	5.59

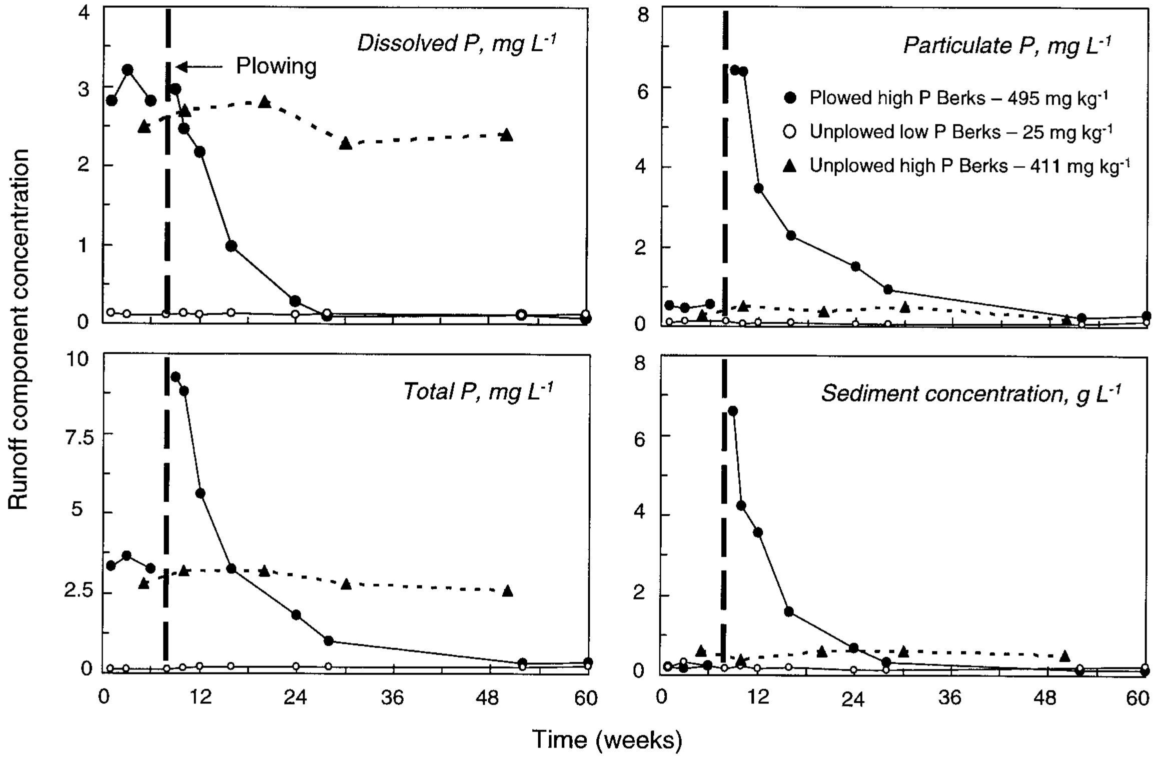

Fig. 6. Concentration of sediment and dissolved, particulate, and total P in overland flow before and after plowing a high-P Berks soil (495 mg kg^{-1} Mehlich-3 P) and from an unplowed low-P (25 mg kg^{-1} Mehlich-3 P) and high-P Berks soil (411 mg kg^{-1} Mehlich-3 P).

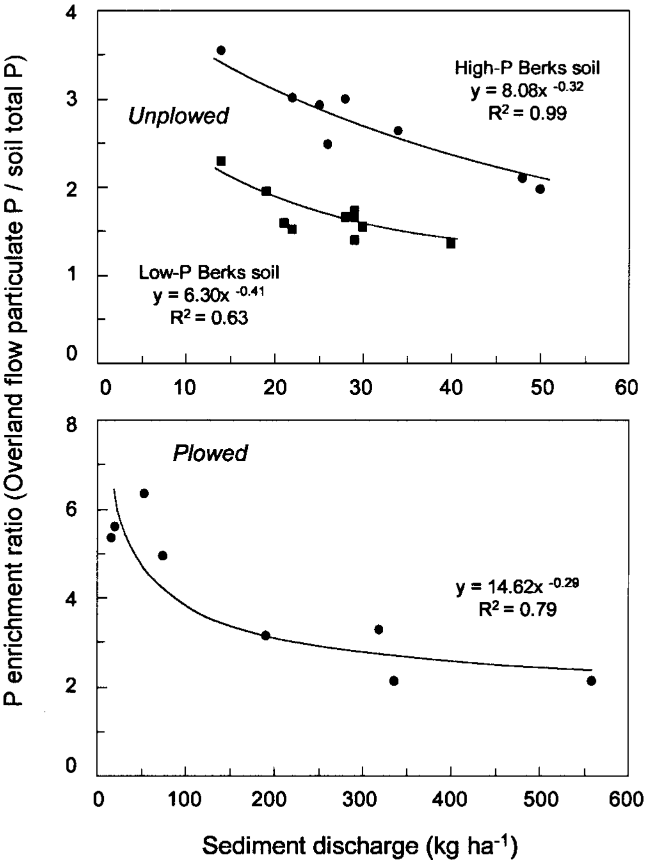

Fig. 7. Relationship between particulate enrichment and sediment discharge of overland flow before and after plowing a high-P Berks soil (495 mg kg^{-1} Mehlich-3 P) and unplowed low-P (25 mg kg^{-1} Mehlich-3 P) and high-P Berks soil (411 mg kg^{-1} Mehlich-3 P).

L^{-1}) (Fig. 6). However, particulate P increased dramatically after plowing. This increase can be attributed to a 30-fold rise in sediment concentration of overland flow (0.22–6.58 g L^{-1}). The greater sediment and associated P discharge occurred in spite of a lower overland flow volume after plowing (17 L) than before (31 L) (Table 4), likely due to a greater infiltration rate afforded by plowing (Gaynor and Findlay, 1995; Soileau et al., 1994).

With time after plowing, there was a steady decline in overland flow P and sediment concentration as orchardgrass became established, protecting the soil surface from P release and soil detachment and entrainment (Fig. 6). In contrast, there was no decrease in the concentration of P in overland flow from the unplowed high P Berks soil (Fig. 6). One year after plowing, dissolved P (0.07 mg L^{-1}) and particulate P (0.28 mg L^{-1}) concentrations were much lower than before plowing (2.90 and 0.50 mg L^{-1}) and from the unplowed high P Berks plot (2.40 and 0.52 mg L^{-1}), but elevated compared with low-P plot concentrations (0.025 and 0.076 mg L^{-1}). Further, overland flow volumes were similar to preplowing and unplowed plot volumes about 20 wk after plowing (28 wk time in Table 4). The loss of P and sediment in overland flow showed similar trends to concentration (Table 4).

The effect of plowing on particulate P entrainment in overland flow and the erosional process was evaluated by calculating the P enrichment ratio (PER) as the P concentration of sediment discharged (mg particulate P kg sediment^{-1}) divided by that of source soil (mg total P kg soil^{-1}). Phosphorus ERs were greater for overland flow from the high-P plots before plowing (avg. 2.71) than from the low-P unplowed plots (avg. 1.76; Table 4). This is consistent with a general increase in PER with increased soil P concentration (Sharpley, 1985). Immediately following plowing, PER decreased to 2.12, reflecting the greater propensity for sheet erosion with little particle size–sorting during transport (Table 4). With time after plowing, however, there was a gradual increase in PER as vegetative cover increased along with the selective entrainment and transport of finer, P-enriched particles.

For all plots, PER decreased with an increase in sediment discharge of each overland flow event (Fig. 7). This relationship reflects the degree to which particle-size selection and preferential transport occurs with overland flow. As sediment discharge increases, there is less particle-size sorting by overland flow, less clay-sized particles are transported in proportion to total soil loss, and P enrichment, thus, decreases. Clearly, plowing a P-stratified soil and then establishing a grass cover to reduce the risk of P loss in overland flow, influences the amount and P enrichment of eroding particles as well as the release of P from surface soil. Although the increase in subsoil P may enhance downward movement of P, the disruption of contiguous macropores during tillage has been shown to decrease percolation (McGregor et al., 1999; Rhoton et al., 2002).

CONCLUSIONS

The long-term application (9–20 yr) of manure (as dairy, poultry, or swine) increased the Mehlich-3 P concentration of the surface 5 cm of soil compared with soil below this depth. Mixing low-P subsoil with high-P surface soil decreased Mehlich-3 P concentration and increased P sorption capacity relative to surface soil properties. Thus, mixing of surface and subsoil material, as would occur during plowing, has the potential to decrease the risk of P enrichment of overland flow from these soils. Although the increase in P sorption capacity of mixed soil has the potential to more tightly bind P, future P additions as fertilizer or manure should be limited to crop removal to minimize further surface build-up of P. These potential benefits to minimizing overland flow P by plowing highly P-stratified soils, result from the combined effects of dilution of high P surface soil and an increased sorption of P. However, plowing should be considered as a one-time last resort after conservation measures have been implemented. Plowing should not be used again until P-enriched subsoil has been depleted by plant uptake. Repeated plowing could result in an excessive accumulation of P throughout the entire plow depth.

Over time, plowing a P-stratified Berks soil decreased total P loss in overland flow compared with an unplowed high P soil. Even so, the potential long-term benefits of plowing P-stratified soils on overland flow P should be considered along with the near-term exacerbated risk of erosion and associated P loss. Once the vegetative cover became established (orchardgrass in this study) and erosion minimized, particulate P in overland flow was also decreased. The potential of plowing a given P-stratified soil on overland flow P may be determined from the weighted mean Mehlich-3 P concentration of surface and subsoil samples.

This combined laboratory incubation and field study demonstrates the potential benefits of plowing P-stratified soils, as long as erosion is minimized after plowing. Thus, plowing P-stratified soils may reduce the long-term loss of P in overland flow and provide landowners an additional option in keeping these soils in production under P-based nutrient management strategies.

REFERENCES

Beegle, D.B. 2001. Soil fertility management. p. 19–46. *In* N. Serotkin and S. Tibbetts (ed.) The agronomy guide, 2001–2002. Publications Distribution Center, Pennsylvania State Univ., University Park, PA.

Bremner, J.M., and C.S. Mulvaney. 1982. Nitrogen—total. p. 595–624. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. SSSA and ASA, Madison, WI.

del Campillo, M.C., S.E.A.T.M. van der Zee, and W.H. van Riensmsdijk. 1996. Systematic bias in measuring intensities by selective extraction of bulked samples. Commun. Soil Sci. Plant Anal. 27:1829–1841.

Gaynor, J.D., and W.I. Findlay. 1995. Soil and phosphorus loss from conservation and conventional tillage in corn production. J. Environ. Qual. 24:734–741.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. SSSA and ASA, Madison, WI.

Guertal, E.A., D.J. Ekert, S.J. Traina, and T.J. Logan. 1991. Differential phosphorus retention in soil profiles under no-till crop production. Soil Sci. Soc. Am. J. 55:410–413.

Halvorson, A.D., and A.L. Black. 1985. Fertilizer phosphorus recovery after seventeen years of dryland cropping. Soil Sci. Soc. Am. J. 49:933–937.

Hooker, M.L., R.E. Gwin, G.M. Herron, and P. Gallagher. 1983. Effects of long-term annual applications of N and P on corn grain yields and soil chemical properties. Agron. J. 75:94–99.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. J. Environ. Qual. 23:139–147.

Kleinman, P.J.A., and A.N. Sharpley. 2002. Estimating soil phosphorus sorption saturation from Mehlich-3 data. Commun. Soil Sci. Plant Anal. 33:1825–1839.

Kunishi, H.M., A.W. Taylor, W.R. Heald, W.J. Gburek, and R.N. Weaver. 1972. Phosphate movement from an agricultural watershed during two rainfall periods. J. Agric. Food Chem. 20:900–905.

McCollum, R.E. 1991. Buildup and decline in soil phosphorus: 30-year trends on a Typic Umprabuult. Agron. J. 83:77–85.

McDowell, R.W., A.N. Sharpley, and A.T. Chalmers. 2002. Land use and flow regime effects on phosphorus chemical dynamics in the fluvial sediment of the Winooski River, Vermont. Ecol. Eng. 18:477–487.

McDowell, R.W., A.N. Sharpley, and G. Folmar. 2001. Phosphorus export from an agricultural watershed: Linking source and transport mechanisms. J. Environ. Qual. 30:1587–1595.

McGregor, K.C., R.F. Cullum, and C.K. Mutchler. 1999. Long-term management effects on runoff, erosion, and crop production. Trans. ASAE 22:100–104.

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

Morrison, J.E., and F.W. Chichester. 1994. Tillage system effects on soil and plant nutrient distributions in Vertisols. J. Prod. Agric. 7:364–373.

Murphy, J., and J.P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. Anal. Chim. Acta 27:31–36.

Nair, P.S., T.J. Logan, A.N. Sharpley, L.E. Sommers, M. Tabatabai, and T.L. Yuan. 1984. Interlaboratory comparison of a standardized phosphorus adsorption procedure. J. Environ. Qual. 13:591–595.

National Phosphorus Research Project. 2002. National Phosphorus Research Project [Online]. [1 p.] Available at http://pswmru.arsup.psu.edu (verified 25 Mar. 2003). USDA-ARS, Pasture Systems and Watershed Management Research Unit, University Park, PA.

Oloya, T.O., and T.J. Logan. 1980. Phosphate desorption from soils and sediments with varying levels of extractable phosphate. J. Environ. Qual. 9:526–531.

Pezzarossa, B., M. Barbafieri, A. Benetti, G. Petruzzelli, M. Mazzoncini, E. Bonari, and M. Pagliai. 1995. Effects of conventional and alternative management systems on soil phosphorus content, soil structure, and corn yield. Commun. Soil Sci. Plant Anal. 261:2869–2885.

Pierson, S.T., M.L. Cabrera, G.K. Evanylo, H.A. Kuykendall, C.S. Hoveland, M.A. McCann, and L.T. West. 2001. Phosphorus and ammonium concentrations in surface runoff from grasslands fertilized with broiler litter. J. Environ. Qual. 30:1784–1789.

Pote, D.H., T.C. Daniel, D.J. Nichols, A.N. Sharpley, P.A. Moore, Jr., D.M. Miller, and D.R. Edwards. 1999. Relationship between phosphorus levels in three Ultisols and phosphorus concentrations in runoff. J. Environ. Qual. 28:170–175.

Rehm, G.W., G.W. Randall, A.J. Scobbie, and J.A. Vetsch. 1995. Impact of fertilizer placement and tillage system on phosphorus distribution in soil. Soil Sci. Soc. Am. J. 59:1661–1665.

Rhoton, F.E., M.J. Shipitalo, and D.L. Lindbo. 2002. Runoff and soil loss from Midwestern and Southeastern U.S. silt loam soils as affected by tillage practice and soil organic matter. Soil Tillage Res. 66:1–11.

Sharpley, A.N. 1985. The selective erosion of plant nutrients in runoff. Soil Sci. Soc. Am. J. 49:1527–1534.

Sharpley, A.N. 1999a. Agricultural phosphorus, water quality, and poultry production: Are they compatible? Poult. Sci. 78:660–673.

Sharpley, A.N. 1999b. Phosphorus availability. Section D. p. 18–38. *In* M. Sumner (ed.) Handbook of soil science. CRC Press, Boca Raton, FL.

Sharpley, A.N., P.J.A. Kleinman, R.J. Wright, T.C. Daniel, B. Joern, R. Parry, and T. Sobecki. 2002. The National Phosphorus Project: Addressing the interface of agriculture and environmental phosphorus management in the USA. Section 2.3 Indicators for environmental performance. p. 95–100. *In* J. Steenvoorden et al. (ed.) Agricultural effects on ground and surface waters: Research at the edge of science and society. International Assoc. of Hydrological Sciences Publ. no. 273. IAHS Press, Wallingford, UK.

Sharpley, A.N., R.G. Menzel, S.J. Smith, E.D. Rhoades, and A.E. Olness. 1981. The sorption of soluble phosphorus by soil material during transport in runoff from cropped and grassed watersheds. J. Environ. Qual. 10:211–215.

Sharpley, A.N., and S.J. Smith. 1994. Wheat tillage and water quality in the Southern Plains. Soil Tillage Res. 30:33–38.

Sharpley, A.N., S.J. Smith, and R. Bain. 1993. Effect of poultry litter application on the nitrogen and phosphorus content of Oklahoma soils. Soil Sci. Soc. Am. J. 57:1131–1137.

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. J. Environ. Qual. 27:277–293.

Soileau, J.M., J.T. Touchton, B.F. Hajek, and K.H. Yoo. 1994. Sediment, nitrogen, and phosphorus runoff with conventional- and conservation-tillage cotton in a small watershed. J. Soil Water Conserv. 49:82–89.

SPSS Inc. 1999. SPSS. Version 10.0. Chicago, IL.

Syers, J.K., M.G. Browman, G.W. Smillie, and R.B. Corey. 1973.

Phosphate sorption by soils evaluated by the Langmuir adsorption equation. Soil Sci. Soc. Am. Proc. 37:358–363.

Taylor, A.W., and H.M. Kunishi. 1971. Phosphate equilibria on stream sediment and soil in a watershed draining an agricultural region. Agric. Food Chem. 19:827–831.

Wagar, B.I., J.W.B. Stewart, and J.O. Moir. 1986. Changes with time in the form and availability of residual fertilizer phosphorus on chernozemic soils. Can. J. Soil Sci. 66:105–119.

Weil, R.R., P.W. Benedetto, L.J. Sikora, and V.A. Bandel. 1988. Influence of tillage practices on phosphorus distribution and forms in three Ultisols. Agron. J. 80:503–509.

Weill, A.N., G.R. Mehuys, and E. McKyes. 1990. Effect of tillage reduction and fertilizer type on soil properties during corn (*Zea mays* L.) production. Soil Tillage Res. 17:63–76.

Zhang, H., W. Raun, J. Hattey, G. Johnson, and N. Basta. 2002. Oklahoma State University soil test interpretations. Ext. Fact Sheet F-2225. Oklahoma State Univ. Coop. Ext. Service, Div. of Agric. Sciences and Natural Resources, Stillwater, OK.