Relationship of Soil Test Phosphorus and Sampling Depth to Runoff Phosphorus in Calcareous and Noncalcareous Soils

H. A. Torbert,* T. C. Daniel, J. L. Lemunyon, and R. M. Jones

ABSTRACT

A study was initiated to investigate the relationship between soil test P and depth of soil sampling with runoff losses of dissolved molybdate reactive phosphorus (DMRP). Rainfall simulations were conducted on two noncalcareous soils, a Windthorst sandy loam (fine, mixed, thermic Udic Paleustalf) and a Blanket clay loam (fine, mixed, thermic Pachic Argiustoll), and two calcareous soils, a Purves clay (clayey, smectitic, thermic Lithic Calciustoll) and a Houston Black clay (fine, smectitic, thermic Udic Haplustert). Soil (0- to 2.5-, 0- to 5-, and 0- to 15-cm depths) and runoff samples were collected from each of the four soils in permanent pasture exhibiting a wide range in soil test P levels (as determined by Mehlich III and distilled water extraction) due to prior manure applications. Simulated rain was used to produce runoff, which was collected for 30 min. Good regression equations were derived relating soil test P level to runoff DMRP for all four soil types, as indicated by relatively high r^2 values (0.715 to 0.961, 0- to 5-cm depth). Differences were observed for the depth of sampling, with the most consistent results observed with the 0- to 5-cm sampling depth. Runoff DMRP losses as a function of the concentration of P in soil were lower in calcareous soils (maximum of 0.74 mg L^{-1}) compared with noncalcareous soils (maximum of 1.73 mg L^{-1}). The results indicate that a soil test for environmental P could be developed, but it would require establishing different soil test P level criteria for different soils or classes of soils.

Recently, scientists and resource managers have become concerned that nonpoint additions of nutrients, especially P, to watersheds may negatively influence water quality. In a 1998 USEPA report, agricultural nonpoint source pollution was estimated to cause 60, 50, and 34% of river, lake, and estuarine impairment, respectively (Parry, 1998). These concerns have been stimulated by blooms of the toxic dinoflagellate algae *Pfiesteria piscicidia* that caused fish kills and human illnesses in the Chesapeake Bay area and by the 1.25 million ha hypoxic (low dissolved oxygen) zone in the Gulf of Mexico (USEPA, 2000).

The greatest potential for nonpoint P contribution to surface waters usually occurs in watersheds with intensive animal production (Duda and Finan, 1983). Manure collected from concentrated animal feeding operations (CAFO) has traditionally been applied to fields near the operation because this is a practical means of both improving soil physical conditions and providing needed plant nutrients for crop production. However, long-term manure application to soils at rates in excess of crop uptake can result in elevated soil P levels (Sharpley et al., 1998; Sims, 1993; Snyder et al., 1993). The N to P ratio of animal manure ranges from 2:1 to 8:1, depending on animal species (Eck and Stewart, 1995). This N to P ratio is much narrower than is needed for crop production, resulting in an overapplication of P and a buildup of soil P levels over time (Sharpley et al., 1996).

Previous research has shown that the loading of P in excess of plant needs directly influences the amount of P found in soil and in runoff (Sharpley, 1995; Sharpley et al., 1977, 1996; Daniel et al., 1994; Pote et al., 1996). Research by Edwards et al. (1993) has shown that the contribution of P from soils with elevated levels of soil test P is potentially more important and difficult to manage than improper land application of animal manure. This study found that elevated soil test P levels were responsible for 65 to 90% of annual P loss from the watershed even when a major surface runoff event occurred 1 d after manure was applied to fescue (*Festuca arundinacea* Schreb.) pasture.

Recent USEPA draft guidelines for manure applications for CAFOs limit application to "threshold P holding capacity of all major soil types within the land application areas" (USDA and USEPA, 1998); however, the threshold P levels of soils are yet to be developed. Recent research has shown that the level of soil P is directly related to runoff losses of P (Sharpley, 1995; Sharpley et al., 1977, 1996; Daniel et al., 1994; Pote et al., 1996), which would indicate that a threshold level could be developed, but work by Pote et al. (1999) and Sharpley et al. (1998) demonstrated that the relationship between the level of soil P and runoff P varied markedly depending on the soil type. Further, it cannot be assumed that soil tests designed for crop production can be used to predict surface runoff enrichment potential.

Using the relationship of soil test P to runoff losses of P could be a valuable management tool for protecting watersheds from excessive nutrient loading. However, the potential of these relationships has not been fully developed, especially for calcareous soils. The objective of this project was to examine the relationships between soil test P levels and runoff losses of P for benchmark soils in the Bosque River watershed and to examine the practical aspects of the data (i.e., depth of sampling and P extractant used) for potential use in development of a soil test for environmental P losses.

MATERIALS AND METHODS

Rainfall simulations were conducted on four soils representative of the major soil types in the Bosque River basin in Texas. The soils studied included two noncalcareous soils, a

H.A. Torbert, USDA-ARS National Soil Dynamics Laboratory, 411 S. Donahue Dr., Auburn, AL 36832-5806. T.C. Daniel, 115 Plant Sci. Bldg., Crop, Soil and Environmental Science Dep., Univ. of Arkansas, Fayetteville, AR 72701. J.L. Lemunyon, USDA-NRCS, P.O. Box 6567, Ft. Worth, TX 76115. R.M. Jones, Texas A&M University Agric. Research and Extension Center, Stephenville, TX 76401. Received 9 Oct. 2001. *Corresponding author (atorbert@ars.usda.gov).

Table 1. Selected soil characteristics for the respective soils.†

Series	Soil Subgroup	Surface textures	Horizon	Depth	CaCO₃	Organic C	pH	Clay	Silt	Sand
				cm	—— g kg⁻¹ ——			—— kg 100 kg⁻¹ ——		
Houston Black	Udic Haplustert	clay	Ap	0–18	280	15.0	8.0	57.4	35.7	7.3
			All	18–48	300	12.8	8.3	55.3	39.3	5.4
			All	48–71	300	10.5	8.2	58.0	37.1	4.9
Windthorst	Udic Paleustalf	sandy loam	Ap1	0–8	10	16.5	7.1	25.4	10.9	63.7
			Ap2	8–17	10	18.1	7.3	25.1	11.2	63.7
			Bt1	17–40	ND‡	3.9	7.0	34.6	11.9	53.5
			Bt2	40–68	ND	2.1	7.0	31.2	14.1	54.7
Blanket	Pachic Argiustoll	clay loam	Ap	0–13	30	17.5	7.9	21.1	23.4	55.5
			Ap2	13–28	150	12.3	8.0	26.2	26.6	47.2
			Bt1	28–48	trace	15.9	7.9	41.7	42.0	16.3
			Btk1	48–64	40	13.4	7.8	42.9	40.5	16.6
Purves	Lithic Calciustoll	clay	Ap	0–6	400	24.9	8.0	29.3	39.5	31.2
			Bw	6–30	340	17.4	7.9	34.1	38.9	27.0
			Bw/R	30–45	490	17.4	7.9	33.4	35.3	31.3
			R/Bw	45–60	660	15.1	8.0	28.4	31.8	39.8

† Characteristics determined by standard USDA Natural Resources Conservation Service soil description techniques.
‡ Not detected.

Windthorst sandy loam and a Blanket clay loam, and two calcareous soils, a Purves clay and a Houston Black clay. After appropriate sites for each soil had been identified, soils in the immediate area were described according to USDA Natural Resources Conservation Service field protocols (USDA Natural Resources Conservation Service, 1996). Selected soil characteristics are given in Table 1. Soils at each location were under permanent Bermuda grass [*Cynodon dactylon* (L.) Pers.] pasture.

At each soil site, six surface runoff plots were constructed, having dimensions of 2 by 3 m, with the long axis oriented down the slope. Slopes of the plots were approximately 5%. The plots were bordered to isolate surface runoff and a collection gutter was placed at the downslope edge of the plot to divert surface runoff to a pit where surface runoff samples could be collected.

At each site, a range in the level of soil test P was established by surface application of dairy manure from a local dairy operation. A target range of soil test P levels of 0 (ambient), 60, 120, 180, 240, and 360 mg kg⁻¹ was used. Manure was applied by evenly hand-spreading over the plot area. Following application of dairy manure over an 18-mo period, a time period of approximately 6 mo was allowed before initiation of rainfall simulation so that the effect of surface manure application on runoff P concentration would be minimized. At each site, the grass was maintained by periodic mowing through the growing season.

A composite soil sample (15 cores) was collected from each plot immediately after simulated rain applications to permit correlation of soil test and surface runoff P levels. Soil cores were taken at 0- to 2.5-, 0- to 5-, and 0- to 15-cm depths. Soil test P was determined by Mehlich III (Mehlich, 1984) and the distilled water methods (Pote et al., 1996; 1 g of soil and 25 mL distilled water shaken for 1 h and filtered through a 0.45-μm membrane). Soil extracts were analyzed colorimetrically for PO₄–P concentration using a Technicon Autoanalyzer (Bran+Luebbe, Buffalo Grove, IL). Soil samples taken at 0 to 5 cm and analyzed by the Mehlich III method were used to establish the soil test P range.

The scientific validity of using the rainfall simulator for runoff research work has been well documented (Meyer, 1965; Andraski et al., 1985; Edwards et al., 1992; Sharpley, 1995). Surface runoff generation and sample collection followed the procedures outlined by Edwards and Daniel (1993a,b) and Pote et al. (1996). Briefly, a rain simulator was used to generate 30 min of surface runoff from each plot by applying rain at 50 mm h⁻¹ intensity. At all sites, source water was tested for soil dispersion with the soil for that site, with no soil dispersion being observed. At the Windthorst, Purves, and Blanket sites, surface runoff samples were collected manually at 5-min intervals during the runoff event, beginning 2.5 min after the start of continuous surface runoff (six discrete samples, plot, rain). The sample volumes and the times required to collect them were recorded and used to construct a flow-weighted composite sample from the six discrete samples. At the Houston Black site, the first 30 min of runoff was collected by pumping runoff water from the collection buckets to barrels. The water collected in the barrels was weighed and mixed, and aliquots were taken for analysis. The grass surface was mowed before rainfall simulation at all sites.

Runoff samples were filtered through a 0.45-μm membrane, acidified to pH 2 with HCl, and frozen until analyzed for DMRP colorimetrically using the automated ascorbic acid reduction method (Pote and Daniel, 2000) with a Technicon Autoanalyzer.

Rainfall simulations were repeated three times on each of the six soil test P level plots at each of the four soil type sites, so that regression analysis could be used to evaluate the relationship between soil test P and surface runoff P. Analysis of variance on runoff P measurements was performed on the data combined across the four soil types. In the analysis, treatments for soil test P level was a continuous linear effect measured by a slope parameter and the interaction of soil type and soil test P treatments allowed the slope to be different for each soil type. The error for the analysis of variance consisted of two parts, the lack of fit from fitting a linear regression to the treatment means and a subsampling error from the three rainfall simulations on each plot. This error was used to compare slopes between the four sites with different soil types (Milliken and Johnson, 2002). The analysis was used to determine if (i) a significant relationship exists between soil test and surface runoff P levels for each of the soils and (ii) the relationship between soil test and surface runoff P is the same between soils. Significance was declared at an established a priori level of $P \leq 0.10$.

Statistical analysis was performed using the Mixed procedure in SAS (SAS Institute, 1996). Soil type, soil test P level, and soil type × soil test P level were fixed effects with soil test P treatments defined as a continuous linear variable. Lack of fit and residual subsampling error were random effects. Contrast statements were used to make all possible comparisons between the slopes. The r^2 values reported are based on
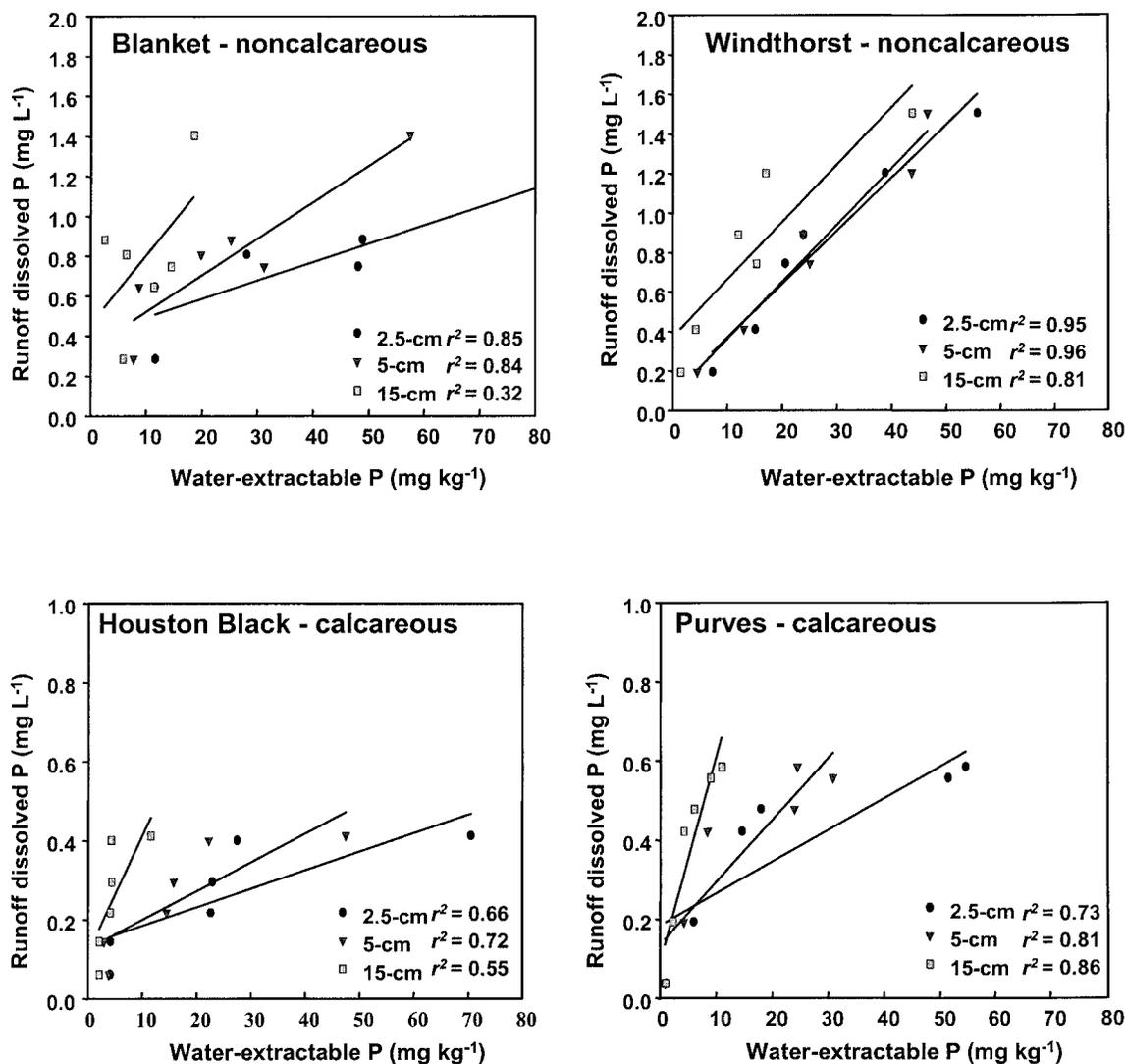
Fig. 1. The relationship between water-extractable P concentration and dissolved molybdate reactive P in runoff for Blanket, Windthorst, Houston Black, and Purves soil.

fitting a straight line through the means for each soil type. Analysis was performed on all three sampling depths for both Mehlich III and distilled water soil test P methods.

RESULTS

The soils used in this study were very different with respect to soil texture and $CaCO_3$ content (Table 1), especially in the upper few centimeters of soil, which is expected to have the greatest influence on runoff P concentrations. While $CaCO_3$ is present in all four soils, levels in the surface horizon of the Houston Black and Purves soils (considered calcareous) are 10-fold higher than the Windthorst and the Blanket soils (Table 1).

Soil samples collected at the four locations indicated that the concentrations of extractable P (Mehlich III at the 0- to 5-cm depth) were reasonably close to the target levels of 0 (ambient), 60, 120, 180, 240, and 360 mg kg^{-1}. In addition, the relative differences in P concentrations for treatment plots could be detected with both the

Mehlich III and water-extractable P techniques at all three soil depths.

Analysis of runoff P concentrations across all four soil types ranged from 0.023 to 1.73 mg L^{-1} for DMRP and from 0.044 to 1.8 mg L^{-1} for total P. For all soils, runoff P concentrations increased as the level of soil test P increased. However, the amount of particulate P (particulate P = total P − DMRP) in runoff remained relatively constant with increasing levels of P in runoff and contributed a very small portion of the total P in runoff at the higher levels of runoff P observed. Since the greatest potential for increased eutrophication of surface water results from DMRP components (Pote and Daniel, 2000), regression analysis presented here will be for DMRP.

It has been speculated that a "change point" (Klein-man et al., 2000; McDowell and Sharpley, 2001) may exist for soil test P concentrations where increasing P application (i.e., manure application) contributes in-creasing concentrations of DMRP to runoff. Within the
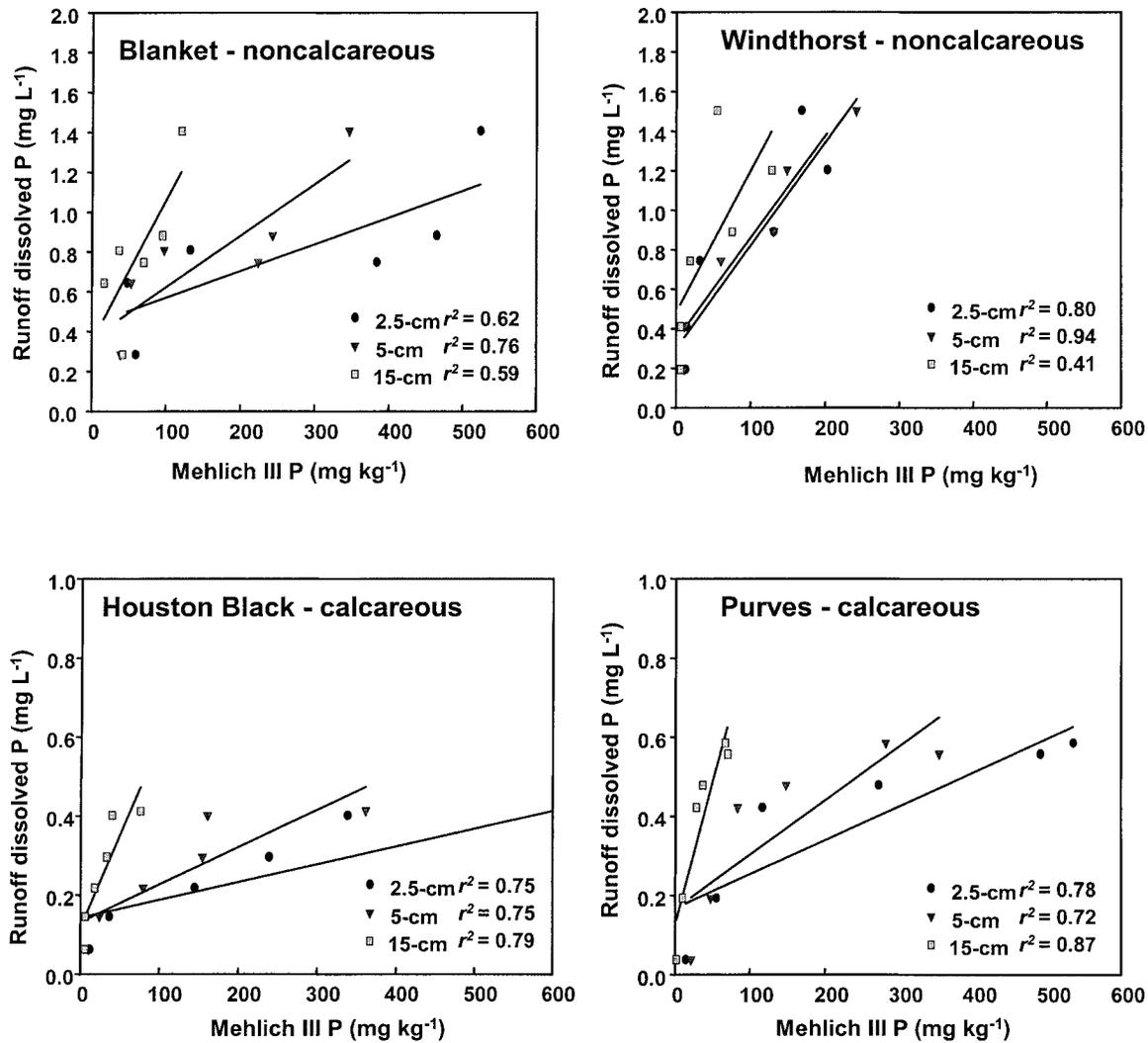
Fig. 2. The relationship between Mehlich III–extractable P concentration and dissolved molybdate reactive P in runoff for Blanket, Windthorst, Houston Black, and Purves soil.

range of soil test P used in this study (0–360 mg kg^{-1}), no breakpoints for soil test P concentrations were observed. The equations developed for predicting DMRP losses by soil test P levels were all linear. This was true for all four soil types and for all three soil depths. This indicated that for these soil types either a breakpoint does not exist or that it is at much higher soil test P levels than were used in this study.

Soil Depth

Results for the analysis of water- and Mehlich III–extractable P regressed against DMRP losses in runoff are shown in Fig. 1 and 2 and regression equations for these lines are presented in Tables 2 and 3. Regression lines demonstrate that a strong relationship exists between soil test P and DMRP in surface runoff with both soil test extractions using water (Fig. 1) and Mehlich III (Fig. 2). Likewise, significant regression lines could be derived for all three soil depths and at all four soil types (Fig. 1 and 2). While differences were observed between the two extractants for soil depth and soil type, overall, both extractants worked well for developing

predictive equations relating runoff losses of DMRP to soil test P (as indicated by r^2 values, Tables 2 and 3). While the relative values of the axes were greatly different, the regression equations developed for the four soils and three soil depths were similar for soil test P and soil depth responses. Similar results have been reported by others (Pote et al., 1999; Sharpley et al., 1998) and our results are further evidence that an environmental soil test can be developed that relates the level of P measured in soil to the amount susceptible to losses in surface runoff.

While similar, significant regression equations were observed for all four soils and for all three soil depths (Tables 2 and 3), examination of the differences and similarities between these regression lines can provide some indications as to the best soil test for P relating to potential environmental loss of P. For example, while the relative response was different between the four soil types, the relative response between the four soil types for changing soil depth was consistent (Fig. 1 and 2). The greater the soil depth, the steeper the curve response to increasing soil test P. We believe this is primarily a

Table 2. Predictive equations relating runoff dissolved molybdate reactive phosphorus (DMRP) to water-extractable soil phosphorus (P_{ex}).†

Soil type	Regression equation	r^2
	0–2.5 cm	
Blanket	DMRP = 0.4013 + 9.194 × 10^{-3} P_{ex}	0.849a
Windthorst	DMRP = 0.1000 + 2.695 × 10^{-2} P_{ex}	0.948a
Houston Black	DMRP = 0.1379 + 4.681 × 10^{-2} P_{ex}	0.659b
Purves	DMRP = 0.1846 + 8.034 × 10^{-3} P_{ex}	0.725a
	0–5 cm	
Blanket	DMRP = 0.3387 + 1.823 × 10^{-2} P_{ex}	0.844a
Windthorst	DMRP = 0.07269 + 2.881 × 10^{-2} P_{ex}	0.961ab
Houston Black	DMRP = 0.1267 + 7.275 × 10^{-3} P_{ex}	0.717c
Purves	DMRP = 0.1352 + 1.574 × 10^{-2} P_{ex}	0.813b
	0–15 cm	
Blanket	DMRP = 0.4577 + 3.433 × 10^{-2} P_{ex}	0.322a
Windthorst	DMRP = 0.3712 + 2.906 × 10^{-2} P_{ex}	0.813a
Houston Black	DMRP = 0.1171 + 2.944 × 10^{-2} P_{ex}	0.552a
Purves	DMRP = 0.09146 + 5.159 × 10^{-2} P_{ex}	0.863a

Significance level ($P > F$)
from analysis of variance

	Source‡		
	0–2.5 cm	0–5 cm	0–15 cm
Soil P concentration	<0.0001	<0.0001	0.0027
Soil type	NS§	NS	NS
Soil P concentration × soil type	0.0004	0.0022	NS

† Equations not followed by a common letter are significantly different based on pair-wise F test for common slopes. Significance is declared at $P \le 0.10$.
‡ Soil type test H0: Intercepts are same for all soil types. Soil P concentration test H0: Average slope = 0. Soil P concentration test H0: Slopes are equal for all soil types.
§ Not significant ($P \le 0.10$).

Table 3. Predictive equations relating runoff dissolved molybdate reactive phosphorus (DMRP) to Mehlich III–extractable soil phosphorus (P_{ex}).†

Soil type	Regression equation	r^2
	0–2.5 cm	
Blanket	DMRP = 0.4363 + 1.34 × 10^{-3} P_{ex}	0.616a
Windthorst	DMRP = 0.3433 + 5.132 × 10^{-3} P_{ex}	0.800ab
Houston Black	DMRP = 0.1432 + 4.48 × 10^{-4} P_{ex}	0.745c
Purves	DMRP = 0.1680 + 8.55 × 10^{-4} P_{ex}	0.776b
	0–5 cm	
Blanket	DMRP = 0.3637 + 2.587 × 10^{-3} P_{ex}	0.757b
Windthorst	DMRP = 0.3003 + 5.189 × 10^{-3} P_{ex}	0.938ab
Houston Black	DMRP = 0.1318 + 9.44 × 10^{-4} P_{ex}	0.754c
Purves	DMRP = 0.1657 + 1.37 × 10^{-3} P_{ex}	0.715a
	0–15 cm	
Blanket	DMRP = 0.3427 + 7.153 × 10^{-3} P_{ex}	0.589a
Windthorst	DMRP = 0.4811 + 7.121 × 10^{-3} P_{ex}	0.411a
Houston Black	DMRP = 0.1191 + 4.657 × 10^{-3} P_{ex}	0.790a
Purves	DMRP = 0.1310 + 7.044 × 10^{-3} P_{ex}	0.865a

Significance level ($P > F$)
from analysis of variance

	Source‡		
	0–2.5 cm	0–5 cm	0–15 cm
Soil P concentration	<0.0001	<0.0001	0.0010
Soil type	NS§	NS	NS
Soil P concentration × soil type	0.0031	0.0008	NS

† Equations not followed by a common letter are significantly different based on pair-wise F test for common slopes. Significance is declared at $P \le 0.10$.
‡ Soil type test H0: Intercepts are same for all soil types. Soil P concentration test H0: Average slope = 0. Soil P concentration test H0: Slopes are equal for all soil types.
§ Not significant ($P \le 0.10$).

factor of dilution of the manure P spread on the surface of the established pasture with the inclusion of deeper sampling increments. In this system, the manure P must move through the sod and down through the soil profile. Consequently, the highest concentrations of P were observed in the soil surface and decreased with increasing depth.

The increasing slope of the regression equations with increasing depth of sampling was not as prevalent for the Windthorst soil compared with the other three soil types (Fig. 1 and 2). The Windthorst soil is a sandy loam soil compared with the other three soils, which were clay and clay loams (Table 1). With the sandy soil, manure additions to the soil surface can move through the soil profile more quickly; consequently, there is less dilution effect of the soil test P values. This resulted in a reduction of the relative change in steepness of regression equations for soil depth in the Windthorst soil compared with the other heavier-textured soil types (Fig. 1 and 2).

While not always the case, the best fit for the regression lines for both Mehlich III and water-extractable P was generally observed with soil collected from the 0- to 5-cm depth (as indicated by greatest r^2 values, Tables 2 and 3). It is believed that this was caused by competing phenomena relative to manure application on the soil surface. At the shallow depth (0 to 2.5 cm) there was increased variability of P concentration in the samples, resulting in some variance in how well the regression equations fit the means (with r^2 ranging from 0.616 to 0.948). However, as soil sampling depth increased, there was a dilution of the soil test P concentration, as more

soil that does not directly interact with the surface water runoff is included. As a result, the regression equation tended to become more ineffective in describing the relationship of soil test P to runoff losses of DMRP. This is best demonstrated with the response observed with the Blanket soil, where excellent relationships were measured for the water-extractable P for the 0- to 2.5-cm ($r^2 = 0.849$) and 0- to 5-cm depths ($r^2 = 0.844$), but a poor relationship was measured for the 0- to 15-cm depth ($r^2 = 0.322$).

Statistical techniques (Proc Mixed; SAS Institute, 1996) were used to compare differences between regression equations at each soil depth between the four soil types (Tables 2 and 3). With the water-extractable P, significant differences were observed between the regression equations of the four soil types (or a significant soil P concentration × soil type interaction) for both the 0- to 2.5- and 0- to 5-cm depths but not the 0- to 15-cm depth (Table 2). At the 0- to 15-cm depth, only the soil P concentration level was found to have a significant effect on the regression equations (Table 2). This indicates that the equations for each soil type would be parallel with a different intercept for each soil type. However, given the response observed at the other two soil depths, this response would not seem to be realistic. It is believed that this response at the 0- to 15-cm depth is actually a diminishment in the effectiveness to describe the relationship, with only the strongest component (P concentration) remaining significant compared with the responses observed at the 0- to 2.5- and 0- to 5-cm depths. At the 0- to 15-cm depth, while the clear

relationship between soil test P level and runoff P losses could be observed, differences between the soil types were not significant. This is consistent with research by Sharpley et al. (1978) that indicated that soil P had a lower correlation to surface runoff P with increasing soil-coring depths. While this may be desirable for providing a "one fits all" line for making an environmental P soil test, it would potentially eliminate important differences in soils for management purposes.

At the 0- to 2.5-cm depth, a significant difference was observed for water-extractable P concentration and soil type, but only the Houston Black soil was significantly different from the other three soil types (Table 2). This lack of significance for the other soil types was probably due to increased variability in the P concentration data at the 0- to 2.5-cm depth. At the 0- to 5-cm depth, the Blanket, Houston Black, and Purves soils were all significantly different from each other (Table 2). The Windthorst soil was significantly different from the Houston Black soil, but was only close ($P = 0.135$) to being significantly different from the other two soil types.

Similar results were observed for differences among the regression equations developed for the Mehlich III extractant (Table 3). As with the water-extractable P at the 0- to 15-cm depth, P concentration was the only significant effect observed. However, with the Mehlich III extractant, differences could be observed between soil types at the 0- to 2.5- and 0- to 5-cm depths. This indicates that Mehlich III may be less variable with P concentration data at the 0- to 2.5-cm depth for developing these types of relationships compared with water-soluble P extraction. However, both extractants resulted in a highly significant relationship at the 0- to 5-cm depth, indicating that this may be the best depth for examining DMRP losses regardless of the extractant used. As was seen with the water-extractable P, at the 0- to 5-cm depth, the Blanket, Houston Black, and Purves soils were significantly different and the Windthorst soil was close ($P = 0.131$) to being significantly different from the Purves and Blanket soil types.

Calcareous versus Noncalcareous Soil

Comparison of the four sites indicates another difference among the regression equations. The two calcareous soils have a much lower concentration of DMRP in runoff at all levels of soil test P compared with the two noncalcareous soils. With the noncalcareous soils, DMRP concentration in runoff varies from 0.2 to 1.5 mg L^{-1}, while the DMRP concentration in the calcareous soils started well below 0.2 mg L^{-1} (0.04 and 0.06 mg L^{-1}) and at the highest soil test P level only reached a concentration of 0.6 mg L^{-1}. In fact, the Houston Black soil only reached a value of 0.4 mg L^{-1} at the highest soil test P concentration. These results have important implications for regulations using soil test P values because these relatively large differences in DMRP losses were observed at the same measurement of soil test P using the same laboratory techniques for determination.

Calcareous soils by definition contain sufficient free CaCO$_3$ to effervesce visibly when treated with cold 0.1

Table 4. Predictive equations for relating runoff dissolved molybdate reactive phosphorus (DMRP) to water-extractable soil phosphorus (P_{ex}) for calcareous and noncalcareous soils.†

Soil type	Regression equation	r^2
	0–2.5 cm	
Calcareous	DMRP = 0.1632 + 6.243 × 10^{-3} P_{ex}	0.567a
Noncalcareous	DMRP = 0.3900 + 1.204 × 10^{-2} P_{ex}	0.620b
	0–5 cm	
Calcareous	DMRP = 0.1493 + 1.013 × 10^{-2} P_{ex}	0.549a
Noncalcareous	DMRP = 0.2225 + 2.276 × 10^{-2} P_{ex}	0.873b
	0–15 cm	
Calcareous	DMRP = 0.1005 + 4.218 × 10^{-2} P_{ex}	0.695a
Noncalcareous	DMRP = 0.5817 + 1.798 × 10^{-2} P_{ex}	0.604a

	Significance level ($P > F$) from analysis of variance		
	Source‡		
	0–2.5 cm	0–5 cm	0–15 cm
Soil P concentration	<0.0001	<0.0001	0.0230
Soil type	NS§	NS	0.0288
Soil P concentration × soil type	0.0974	0.0040	NS

† Equations not followed by a common letter are significantly different based on pair-wise F test for common slopes. Significance is declared at $P \leq 0.10$.
‡ Soil type test H0: Intercepts are same for all soil types. Soil P concentration test H0: Average slope = 0. Soil P concentration test H0: Slopes are equal for all soil types.
§ Not significant ($P \leq 0.10$).

M HCl (Soil Science Society of America, 1997). Soluble P will react with Ca in soil to form insoluble minerals such as hydroxyapatite and fluorapatite. Therefore, calcareous soils will probably contain less soluble P at higher levels of total soil P (higher manure application). The presence of free CaCO$_3$ in calcareous soils will probably reduce the amount of soluble P present in soil and prevent it from being released into runoff.

Soil P extractants were developed to measure the amount of P that would be released during the growing season for plant production, therefore, most extractants will dissolve some of the insoluble Ca-phosphate minerals present in soil. The data presented here demonstrate that while the P concentrations present in extractants are directly related to the potential P release into runoff, the relationship can be highly influenced by the presence of soil components that form insoluble P minerals.

While measuring differences between soil types is important, it is necessary to develop a practical soil test P for environmental concerns. Therefore, predictive equations are needed that will work satisfactorily for groups of soils to predict DMRP in runoff. In this study, an attempt was made to develop regression equations by grouping the two calcareous soils and the two noncalcareous soils. The results of this analysis are shown in Tables 4 and 5 and in Fig. 3. Significant regression lines were developed for comparing soils for both the water-extractable and the Mehlich III extractants, but not for all three soil depths. With the Mehlich III data, no significant regression lines could be developed for the 0- to 2.5-cm depth, and the regression equations developed at the 0- to 15-cm depth were not significantly different from each other. However, at the 0- to 5-cm depth, regression equations were developed with reasonable r^2 values and a highly significant soil type effect

Table 5. Predictive equations for relating runoff dissolved molybdate reactive phosphorus (DMRP) to Mehlich III–extractable soil phosphorus (P_{ex}) for calcareous and noncalcareous soils.†

Soil type	Regression equation	r^2
	0–2.5 cm	
Calcareous	NS‡	
Noncalcareous		
	0–5 cm	
Calcareous	DMRP = 0.1486 + 1.176 × 10^{-3} P_{ex}	0.668a
Noncalcareous	DMRP = 0.3550 + 3.395 × 10^{-3} P_{ex}	0.677b
	0–15 cm	
Calcareous	DMRP = 0.1430 + 5.397 × 10^{-3} P_{ex}	0.771a
Noncalcareous	DMRP = 0.6033 + 3.714 × 10^{-3} P_{ex}	0.448a

	Significance level ($P > F$) from analysis of variance		
	Source§		
	0–2.5 cm	0–5 cm	0–15 cm
Soil P concentration	NS	0.0001	0.0130
Soil type	NS	NS	0.0277
Soil P concentration × soil type	NS	0.0025	NS

† Equations not followed by a common letter are significantly different based on pair-wise F test for common slopes. Significance is declared at $P \leq 0.10$.

‡ Not significant ($P \leq 0.10$).

§ Soil type test H0: Intercepts are same for all soil types. Soil P concentration test H0: Average slope = 0. Soil P concentration test H0: Slopes are equal for all soil types.

(Table 5). With the water-extractable P, regression lines could be developed at all depths, but no significant differences were observed with the 0- to 15-cm depth (Table 4). A significant difference was observed between the regression models for the 0- to 2.5 depth, but only at the $\alpha = 0.1$ probability level ($P = 0.097$). A highly significant difference was observed between the two models at the 0- to 5-cm depth ($P = 0.004$) with reasonable r^2 values for the two lines.

DISCUSSION

The data presented in this study indicate significant differences in the potential for runoff losses of DMRP at the same concentration of soil test P between different soil types within the same watershed. Also, the data indicate that there is a potential to group classes of soil types for their soil DMRP loss potential. These differences, if properly described, could be used in tools such as the Phosphorus Index (Lemunyon and Gilbert, 1993) for manure management.

If a soil test for P is to be used as a management tool for land application of manure, soils will need to be grouped into reasonable management categories and reliable predictive equations for potential P loss developed for those soil categories. Work by Pote et al. (1999) indicated that soil physical effects (rainfall infiltration rate) could be useful in this purpose of grouping different soil series. In their work, the difference in predictive equations between soil types were virtually eliminated by accounting for differences between runoff levels. However, these techniques did not work in this study, primarily because of the lower DMRP losses observed in the calcareous soils. However, grouping soils by chemical characteristics (calcareous vs. noncalcareous)
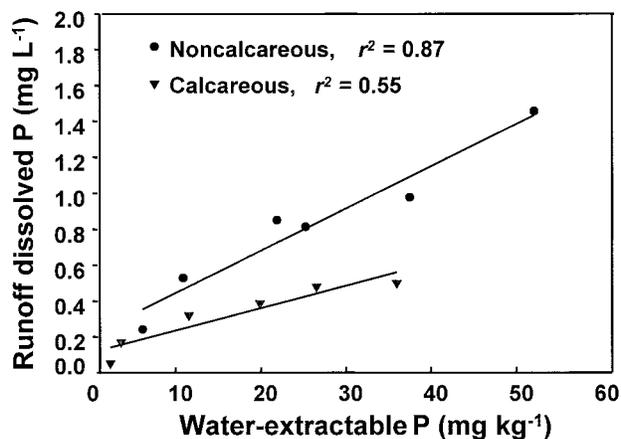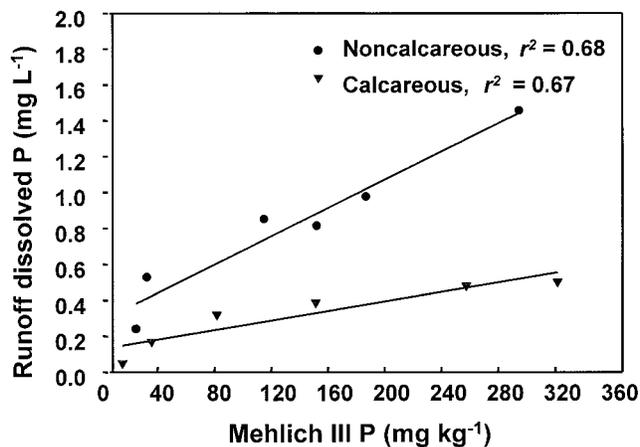

Fig. 3. The relationship between water-extractable and Mehlich III–extractable P concentrations and dissolved molybdate reactive P in runoff for calcareous and noncalcareous soils at the 0- to 5-cm depth.

allowed development of significant predictive equations (Fig. 3).

Differences observed between depth of soil sampling may also be very important in developing a P soil test for environmental response purposes. Besides the physical problem of obtaining a consistent soil sample on the soil surface, soil sampling at the 0- to 2.5-cm depth tended to increase variability, indicating that sampling at this depth may be problematic. For example, with data for the 0- to 2.5-cm depth, there was no significant effect for calcareous vs. noncalcareous soils for the Mehlich III extractant (Table 5). This indicated that the variability inherent at the 0- to 2.5-cm depth may result in difficulties in developing predictive equations that hold up across large numbers of soil types. In addition, soil sampling at the 0- to 2.5-cm depth may be more sensitive to "hot spots" of manure in the production fields.

Likewise, soil sampling at the 0- to 15-cm depth may also be problematic for soil testing for potential environmental P losses. The potential problem with the data developed for the 0- to 15-cm depth is the steepness of the curve, with differences between agronomic response levels and excessive levels being small. The result of a steep response curve is that small differences in soil test P concentration could result in huge differences in interpretation. This would in turn put more pressure on

sampling methods in the field and measuring equipment in the laboratory to assure accuracy of measurements. Since large changes in the field would be measured with small differences in soil test P results, it would be difficult for operators to follow the progress of P enrichment in their fields. In addition, a reduction in the capacity to distinguish difference between soil types may result in difficulty for developing predictive equations over a large grouping of soil types, as indicated by the lower significant levels observed with this depth with the calcareous versus noncalcareous analysis (Tables 3 and 4).

The data indicate that sampling at the 0- to 5-cm depth may result in the best results both from limiting management problems and by increasing the likelihood of developing reliable predictive equations across a large number of soil types. It might be argued that shallow sampling (0 to 5 cm) would be easier to falsify since sampling at a slightly deeper depth would result in a dilution and therefore a reduction in the resulting soil test P. However, the same effects could be accomplished with deeper sampling at the 0- to 15-cm depth. In the end, trust in the integrity of the sampler must be assumed in any sampling scheme developed.

The differences between soil sampling depths would probably not be relative to situations where soil tillage would be conducted, because the mixing of the soil would eliminate or greatly reduce the concentration gradient found when manure is added to the surface and not incorporated. In this case, the 0- to 15-cm depth could provide the best sampling method because it would probably reduce the variability of soil sampling. However, verification of this is needed with similar studies conducted with tilled soil conditions.

The data presented in this study demonstrate two important points: (i) differences exist in soil that may affect the level of DMRP contributed to the environment at the same level of soil test P and (ii) these differences could potentially be used in the management of CAFOs to reduce DMRP levels in runoff. Also, the data demonstrate that there may be chemical or physical characteristics of soils that can be used to develop application criteria in predictive tools such as the Phosphorus Index.

REFERENCES

Andraski, B.J., D.H. Mueller, and T.C. Daniel. 1985. Phosphorus losses in runoff as affected by tillage. Soil Sci. Soc. Am. J. 49: 1523–1527.

Daniel, T.C., A.N. Sharpley, D.R. Edwards, R. Wedepohl, and J.L. Lemunyon. 1994. Minimizing surface water eutrophication from agriculture by phosphorus management. J. Soil Water Conserv. Suppl. 49:30–38.

Duda, A.M., and D.S. Finan. 1983. Influence of livestock on nonpoint source nutrient levels of streams. Trans. ASAE 26:1710–1716.

Eck, H., and B.A. Stewart. 1995. Manure. p. 169–198. In J.E. Rechcigl (ed.) Environmental aspects of soil amendments. Lewis Publ., Boca Raton, FL.

Edwards, D.R., and T.C. Daniel. 1993a. Effects of poultry litter application rate and rainfall intensity on quality of runoff from fescue grass plots. J. Environ. Qual. 22:361–365.

Edwards, D.R., and T.C. Daniel. 1993b. Runoff quality impacts of swine manure applied to fescue plots. Trans. ASAE 36:81–86.

Edwards, D.R., T.C. Daniel, J.F. Murdoch, and P.F. Vendrell. 1993. The Moore's Creek BMP effectiveness monitoring project. Paper 932085. Am. Soc. Agric. Eng., St. Joseph, MI.

Edwards, D.R., L.D. Norton, T.C. Daniel, J.T. Walker, D.L. Ferguson, and G.A. Dwyer. 1992. Performance of a rainfall simulator. Arkansas Farm Res. 41:13–14.

Kleinman, P.J.A., R.B. Bryant, W.S. Reid, A.N. Sharpley, and D. Pimentel. 2000. Using soil phosphorus behavior to identify environmental thresholds. Soil Sci. 165:943–950.

Lemunyon, J.L., and R.G. Gilbert. 1993. Concept and need for a phosphorus assessment tool. J. Prod. Agric. 6:483–486.

McDowell, R.W., and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. J. Environ. Qual. 30:508–520.

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

Meyer, L.D. 1965. Simulation of rainfall for soil erosion research. Trans. ASAE 8:63–65.

Milliken, G.A., and D.E. Johnson. 2002. Analysis of messy data. Volume III: Analysis of covariance. CRC Press, Boca Raton, FL.

Parry, R. 1998. Agricultural phosphorus and water quality: A U.S. Environmental Protection Agency perspective. J. Environ. Qual. 27:258–261.

Pote, D.H., and T.C. Daniel. 2000. Analyzing for dissolved reactive phosphorus in water samples. p. 91–93. In G.M. Pierzynski (ed.) Methods of phosphorus analysis for soils, sediments, residuals, and waters. Southern Coop. Ser. Bull. 396. North Carolina State Univ., Raleigh.

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.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855–859.

SAS Institute. 1996. SAS/STAT user's guide. Version 6.0. 4th ed. SAS Inst., Cary, NC.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. J. Environ. Qual. 24:920–926.

Sharpley, A.N., T.C. Daniel, J.T. Sims, and D.H. Pote. 1996. Determining environmentally sound soil phosphorus levels. J. Soil Water Conserv. 51:160–166.

Sharpley, A.N., J.J. Meisinger, A. Breeuwsma, T. Sims, T.C. Daniel, and J.S. Schepers. 1998. Impacts of animal manure management on ground and surface water quality. p. 173–242. In J. Hatfield (ed.) Effective management of animal waste as a soil resource. Ann Arbor Press, Chelsea, MI.

Sharpley, A.N., J.K. Syers, and R.W. Tillman. 1978. An improved soil-sampling procedure for the prediction of dissolved inorganic phosphate concentrations in surface runoff from pastures. J. Environ. Qual. 7:455–456.

Sharpley, A.N., R.W. Tillman, and J.K. Syers. 1977. Use of laboratory extraction data to predict losses of dissolved inorganic phosphate in surface runoff and tile drainage. J. Environ. Qual. 6:33–36.

Sims, J.T. 1993. Environmental soil testing for phosphorus. J. Prod. Agric. 6:501–507.

Snyder, C.S., S.L. Chapman, W.H. Baker, W.E. Sabbe, and Y.S. McCool. 1993. Changes in Arkansas' sampled acreage testing low and high in soil phosphorus over the last 30 years. Soils and Fertility Information Article 1-93. Univ. of Arkansas Coop. Ext. Serv., Little Rock.

Soil Science Society of America. 1997. Glossary of soil science terms. SSSA, Madison, WI.

USDA Natural Resources Conservation Service. 1996. Soil survey laboratory methods manual. Soil Survey Investigations Rep. 42. USDA-NRCS, Washington, DC.

USDA and USEPA. 1998. Unified national strategy for animal feeding operations. USDA and USEPA, Washington, DC.

USEPA. 2000. National management measures to control nonpoint source pollution from agriculture. USEPA Office of Water, Washington, DC.