

## Soil Characteristics and Phosphorus Level Effect on Phosphorus Loss in Runoff

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### ABSTRACT

The loss of phosphorus (P) in runoff from agricultural soils may accelerate eutrophication in lakes and streams as well as degrade surface water quality. Limited soil specific data exist on the relationship between runoff P and soil P. This study investigated the relationship between runoff dissolved reactive phosphorus (DRP) and soil P for three Oklahoma benchmark soils: Richfield (fine, smectitic, mesic Aridic Argiustoll), Dennis (fine, mixed, active, thermic Aquic Argiudoll), and Kirkland (fine, mixed, superactive, thermic Udertic Paleustoll) series. These soils were selected to represent the most important agricultural soils in Oklahoma across three major land resource areas. Surface soil (0–15 cm) was collected from three designated locations, treated with diammonium phosphate (18–46–0) to establish a wide range of water-soluble phosphorus (WSP) (3.15–230 mg kg<sup>-1</sup>) and Mehlich-3 phosphorus (M3P) (27.8–925 mg kg<sup>-1</sup>). Amended soils were allowed to reach a steady state 210 d before simulated rainfall (75 mm h<sup>-1</sup>). Runoff was collected for 30 min from bare soil boxes (1.0 × 0.42 m and 5% slope) and analyzed for DRP and total P. Soil samples collected immediately before rainfall simulation were analyzed for the following: M3P, WSP, ammonium oxalate P saturation index (PSI<sub>ox</sub>), water-soluble phosphorus saturation index (PSI<sub>wsp</sub>), and phosphorus saturation index calculated from M3P and phosphorus sorption maxima (P<sub>sat</sub>). The DRP in runoff was highly related ( $p < 0.001$ ) to M3P for individual soil series ( $r^2 > 0.92$ ). Highly significant relationships ( $p < 0.001$ ) were found between runoff DRP and soil WSP for the individual soil series ( $r^2 > 0.88$ ). Highly significant relationships ( $p < 0.001$ ) existed between DRP and different P saturation indexes. Significant differences ( $p < 0.05$ ) among the slopes of the regressions for the DRP–M3P, DRP–WSP, DRP–PSI<sub>ox</sub>, DRP–PSI<sub>wsp</sub>, and DRP–P<sub>sat</sub> relationships indicate that the relationships are soil specific and phosphorus management decisions should consider soil characteristics.

THE INFLUX of phosphorus from agricultural surface runoff has accelerated eutrophication of many lakes and streams (Sims et al., 1998; USEPA, 1998; Pote et al., 1999). According to the USEPA (1998), the primary source of nonpoint source (NPS) pollution degrading the quality of stream and lake water is agriculture. As a result, scientists have conducted a considerable amount of research to provide information about P transport processes from agricultural soils.

A better understanding of P transport processes will provide useful information for the development of site-specific P management strategies. The P risk index is a

tool used to assess various landforms and management practices for potential risk of P movement to water bodies (Lemunyon and Gilbert, 1993). The P risk index considers P source and transport factors (Lemunyon and Gilbert, 1993). Many states have developed or are currently in the process of developing state specific P risk indices (Sharpley et al., 2002). Generally, the factors contributing to P loss potential are weighted and the sum of the weighted factors is the derived relative risk index. However, the weights and relative P loss risk index have been derived primarily from professional judgment, as there is limited site-specific data (Lemunyon and Gilbert, 1993).

Many researchers have found that the P content of the surface soil directly influences the loss of P in runoff (Romkens and Nelson, 1974; Daniel et al., 1994). Other researchers have shown significant relationships between soil P and runoff P concentration (Wendt and Alberts, 1984; Sharpley, 1995; Pote et al., 1999; Cox and Hendricks, 2000).

As there is a relationship between runoff P and soil test P, there is a critical soil test P level. Soil test P levels above this critical point will negatively influence water quality. A common soil P–runoff P management strategy is to identify this critical level in soil and prevent further manure or commercial fertilizer P addition. However, research has indicated that a universal soil P critical limit will not adequately protect water quality because P loss is not constant across all soils. It has been found that the critical levels and relationships between runoff P and soil P are soil specific and dependent on soil and site characteristics (Daniel et al., 1994; Sharpley et al., 1996; Pote et al., 1999; Cox and Hendricks, 2000). Consequently, it is the goal of many state and federal water quality agencies to identify soil P critical levels for benchmark soils (Daniel et al., 1994).

In a review paper, Sharpley et al. (1996) compared the findings from eight studies and found that the relationship between runoff dissolved reactive phosphorus (DRP) and Bray 1 P varied markedly among soils tested, indicating that soil type influences the relationship between runoff P and soil P. Cox and Hendricks (2000) found that two soils with clay contents of 5 and 32% would require soil Mehlich-3 phosphorus (M3P) values of 253 and >700 mg dm<sup>-3</sup>, respectively, to produce runoff DRP concentrations of 1 mg L<sup>-1</sup>. Using ammonium oxalate–extractable Fe, Al, and P, Hooda et al. (2000) found that ammonium oxalate P saturation index (PSI<sub>ox</sub>) was the most significant soil property for predicting water desorbable P from contrasting soils. There-

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**Abbreviations:** DAP, diammonium phosphate; DRP, dissolved reactive phosphorus; M3P, Mehlich-3 phosphorus; P<sub>sat</sub>, phosphorus saturation index calculated from Mehlich-3 phosphorus and phosphorus sorption maxima; PSI<sub>ox</sub>, ammonium oxalate phosphorus saturation index; PSI<sub>wsp</sub>, water-soluble phosphorus saturation index; S<sub>max</sub>, phosphorus adsorption maximum; STP, soil test phosphorus; TSS, total suspended solids; WSP, water-soluble phosphorus.

**Table 1. Soil classification and chemical and physical characteristics (top 15 cm) of three soil series evaluated.**

Parameter	Soil series		
	Richfield	Dennis	Kirkland
Classification†	fine, smectitic, mesic Ardic Argiustoll	fine, mixed, active, thermic, Acquic Argiudoll	fine, mixed, superactive, thermic Udertic Paleustoll
Location	36°33.4' N, 100°36.1' W	36°20.3' N, 95°40.40' W	35°48.9' N, 97°34.1' W
Mean annual rainfall, mm	430	1030	820
Texture	clay loam	silt loam	loam
Sand, g kg <sup>-1</sup>	210	300	280
Silt, g kg <sup>-1</sup>	450	590	480
Clay, g kg <sup>-1</sup>	340	110	240
Organic matter, g kg <sup>-1</sup>	18.0	20.0	24.0
pH‡	7.6	7.3	5.4
S <sub>max</sub> §, mg kg <sup>-1</sup>	312	189	244

† USDA-NRCS (2001).

‡ Soil pH was measured in a 1:1 soil to deionized water suspension (Thomas, 1996).

§ Phosphorus adsorption maxima calculated from linearized Langmuir adsorption isotherms.

fore, runoff P–soil P relationships used to assess the potential for P loss in runoff will probably have to be soil and site specific (Sharpley, 1995).

While many researchers have illustrated the relationship between runoff P and soil P among a wide range of soils, few have compared multiple soils within one study. Using 10 Oklahoma soils, Sharpley (1995) illustrated soil specific relationships between runoff P and M3P. Conversely, Sharpley found that a single regression equation could describe the relationship between DRP and soil P sorption maxima ( $S_{max}$ ) for all 10 soils investigated. This study suggests that soil P saturation based on sorption maxima determines the potential for P loss in runoff (Sharpley, 1995).

Using three Ultisols, Pote et al. (1999) also found soil specific relationships between runoff DRP and soil water-soluble phosphorus (WSP). Pote also discovered that normalizing runoff DRP to runoff depth (cm) could correct the differences observed between the three evaluated soils. This finding suggests that the relationship between runoff P and soil P is dependent on soil hydrology.

Researchers have shown that the physical and chemical properties of soil may profoundly influence the relationship between runoff P and soil P. Consequently, it is important to differentiate which properties may have the greatest impact on the runoff P–soil P relationship. Such information is essential to the development of a

practical and effective site-specific P risk index assessment and management tool. The objectives of this study were to (i) evaluate the impact of soil P on runoff P in three soil series representative of the most important agricultural soils in Oklahoma across three major land resource areas and (ii) determine the effect of soil physical and chemical properties on runoff P.

## MATERIALS AND METHODS

### Soil Collection and Preparation

Three Oklahoma benchmark soils—Richfield, Dennis, and Kirkland—were selected for this study based on geographic distribution, major land use area, and physical properties (USDA-NRCS, 2001) (Table 1). The soils were selected to represent the most important agricultural soils in Oklahoma across three major land resource areas. The soils were collected from three different agricultural research stations located in eastern, central, and western Oklahoma. At each of these three locations the top 15 cm of soil was collected using a front-end loader. After collection, the soils were sieved through a 19-mm sieve (National Phosphorus Research Project, 2001) to remove rocks and plant materials, then homogenized using an industrial mortar mixer. Four diammonium phosphate (DAP) fertilizer treatments were applied to each soil to reach predetermined M3P levels (Table 2). Dissolved DAP fertilizer treatments were applied using a pressure sprayer during soil homogenization. Fertilizer was added using an esti-

**Table 2. Amount of fertilizer phosphorus added, mean extractable soil phosphorus, and mean phosphorus saturation indexes for each treatment ( $n = 4$ ) after 210 d soil equilibration time.**

Soil series	P added	Mehlich-3 P	Water-soluble P	PSI <sub>ox</sub> ‡	P <sub>sat</sub> §	PSI <sub>WSP</sub> ¶
		(M3P)	(WSP)			
		mg kg <sup>-1</sup>		%		
Richfield	0	27.8a†	4.27a	12.5a	8.90a	1.37a
	235	172b	32.3b	25.6b	55.2b	10.3b
	635	428c	85.0c	50.8c	137c	27.3c
	1135	817d	196d	77.6d	262d	62.9d
Dennis	0	34.8a	3.15a	10.4a	18.4a	1.67a
	225	144b	17.3a	23.9ab	76.3b	9.16a
	625	411c	66.7b	47.4b	218c	35.3b
	1125	925d	230c	91.6c	489d	122c
Kirkland	0	56.1a	3.96a	11.1a	18.4a	1.63a
	180	169b	18.4a	18.9b	76.3b	7.53a
	580	478c	67.2b	36.4c	218c	27.5b
	1080	919d	146c	52.2d	489d	59.8c

† Mean values with the same letter within a soil are not statistically different at an alpha level of 0.05.

‡ Phosphorus saturation index calculated from acid ammonium oxalate data (oxalate P/oxalate Al + oxalate Fe).

§ Phosphorus saturation index calculated from M3P and P sorption maxima (M3P/ $S_{max}$ ).¶ Phosphorus saturation index calculated from water-soluble P and P sorption maxima (WSP/ $S_{max}$ ).

mate of adding 2 mg fertilizer P per kg of soil to raise soil M3P by 1 mg kg<sup>-1</sup>. The treated and mixed soils were placed in 42.25-cm-wide × 100-cm-long × 13.75-cm-high wooden, mesh-bottomed boxes to a depth of 13 cm. There were 48 boxes in total (three soils, four treatments/soil test P levels, and four replications). The soils were frequently irrigated and incubated for 210 d to allow M3P levels to reach a steady state before rainfall simulation took place. Representative soil samples were taken periodically to monitor M3P changes over time. Plants were not grown in the soil boxes throughout the experiment.

### Rainfall Simulation

The rainfall simulation was conducted using a solenoid-operated, variable intensity rainfall simulator based on the design of Miller (1987) over the week of 25 June 2001. The simulator has one TeeJet 1/2 HH SS 50 WSQ nozzle (Spraying Systems, Wheaton, IL) placed in the center of the 3-m-high × 2.8-m-long × 2.3-m-wide aluminum frame. The intensity of the simulated rainfall was controlled by the on-off spraying times (1.3 s on, 0.4 s off) of the nozzle. The pressure of the water supply for the rainfall simulator was calibrated to deliver 75 mm h<sup>-1</sup>, which is in accordance with the protocol recommended by the National Phosphorus Research Project (2001) and equivalent to a 10-yr storm event in north-central Oklahoma (United States Department of Commerce, 1961). The source water for the rainfall simulation was potable tap water, which had an average TP or DRP of 0.07 mg L<sup>-1</sup>.

The boxes were saturated using the rainfall simulator (75 mm h<sup>-1</sup> until ponding was observed, approximately 10 min) and excess water drained naturally 24 h before rainfall simulation. Rainfall was applied to soil boxes on a 5% slope until 30 min of measurable runoff was collected. From each collection container, total runoff volume was recorded for each soil box and a representative runoff sample (500 mL) was obtained for analyses. In addition, an aliquot (500 mL) of well-mixed runoff from one of the replicates for all soils was collected every 5 min throughout the 30 min runoff duration to evaluate changes in runoff volume and P concentration over time. Soil samples were collected from each box before rainfall simulation, air-dried, sieved to pass a 2-mm screen, and analyzed for different forms of P, which were then correlated with runoff P.

### Soil and Runoff Analyses

Mehlich 3-extractable phosphorus (M3P; Mehlich, 1984), water-soluble phosphorus (WSP; Self-Davis et al., 2000), P sorption maxima ( $S_{\max}$ ), ammonium oxalate-extractable phosphorus ( $P_{\text{ox}}$ ), Al ( $Al_{\text{ox}}$ ), and Fe ( $Fe_{\text{ox}}$ ), texture (Gee and Bauder, 1986), soil organic matter (SOM; Ben-Dor and Banin, 1989), and pH (Thomas, 1996) were determined for the three soils series evaluated. Duplicate analyses were conducted on the study soils. Soil characterization results are summarized in Table 1.

Phosphorus adsorption isotherms were determined according to the method of Graetz and Nair (2000). One gram of soil sample was equilibrated with 25 mL 0.0, 0.5, 1.0, 5.0, 10.0, 15.0, and 20.0 mg P L<sup>-1</sup> in 0.01 M CaCl<sub>2</sub> solution in 50-mL centrifuge tubes. The tubes were shaken for 24 h on an end-to-end shaker at 150 oscillations per min (opm). The samples were then centrifuged for 10 min at 5211 × *g* and the supernatant decanted. The P in solution was then quantified colorimetrically using the ascorbic acid method (Kuo, 1996). The amount of P adsorbed was determined by the difference between the initial and final amounts of P in solution. Duplicate analyses were conducted on all study soils.

Phosphorus adsorption isotherms were determined with the linearized form of the Langmuir equation (Eq. [1]):

$$C/S = (1/kS_{\max}) + (C/S_{\max}) \quad [1]$$

where  $S$  = the total amount of P retained, mg kg<sup>-1</sup>;  $C$  = concentration of P after 24 h equilibrium, mg L<sup>-1</sup>;  $S_{\max}$  = P sorption maximum, mg kg<sup>-1</sup>; and  $k$  = a constant related to the bonding energy, L mg<sup>-1</sup> P.

The term  $S_{\max}$  was calculated by regressing  $C/S$  versus  $C$ , where  $C$  is the equilibrium solution P concentration and  $S$  is adsorbed P. The reciprocal of the slope of the linear regression is  $S_{\max}$  (Olsen and Watanabe, 1957; Syers et al., 1973).

Acidified ammonium oxalate-extractable P, Al, and Fe ( $P_{\text{ox}}$ ,  $Al_{\text{ox}}$ ,  $Fe_{\text{ox}}$ ) were determined by shaking 1.5-g samples of soil with 30 mL of 0.5 M (COONH<sub>4</sub>)<sub>2</sub>·H<sub>2</sub>O at pH 3.0 in 50-mL centrifuge tubes (Schoumans, 2000) for 2 h, in the dark, on an end-to-end shaker at 150 opm and centrifuged for 10 min at 5211 × *g*. Supernatants were analyzed for P, Al, and Fe using inductively coupled plasma-atomic emission spectroscopy (ICP-AES). The  $PSI_{\text{ox}}$  was computed using the P, Al, and Fe contents (mmol kg<sup>-1</sup>) according to Eq. [2] (Schoumans, 2000):

$$PSI_{\text{ox}} (\%) = (P_{\text{ox}}/[Fe_{\text{ox}} + Al_{\text{ox}}] \times 100) \quad [2]$$

Another approach proposed by Sharpley (1995) for the estimation of P saturation uses M3P (Mehlich, 1984) and the adsorption maximum ( $S_{\max}$ ) from P adsorption isotherms. It is referred to as  $P_{\text{sat}}$  and is defined as:

$$P_{\text{sat}} (\%) = (M3P/S_{\max}) \times 100 \quad [3]$$

where M3P and  $S_{\max}$  are in mg kg<sup>-1</sup> soil.

Another P saturation index similar to  $P_{\text{sat}}$  ( $PSI_{\text{WSP}}$ ) was computed using WSP according to Eq. [4]:

$$PSI_{\text{WSP}} (\%) = (WSP/S_{\max}) \times 100 \quad [4]$$

Immediately after rainfall simulation, an aliquot of runoff water sample was filtered (0.45 μm) and analyzed colorimetrically (Murphy and Riley, 1962) to determine dissolved reactive phosphorus (DRP) (Pote and Daniel, 2000). Total phosphorus (TP) from each runoff sample was determined by digesting 25 mL of runoff at 175°C with 1 mL concentrated H<sub>2</sub>SO<sub>4</sub> and 5 mL concentrated HNO<sub>3</sub> until a total volume of 1 mL remained (Pote and Daniel, 2000). All digested samples were neutralized and analyzed for P colorimetrically (Murphy and Riley, 1962). Particulate phosphorus (PP) was calculated by subtracting DRP from TP. Runoff TP and DRP loads (mg) were computed by multiplying DRP and TP concentration (mg L<sup>-1</sup>) by total runoff volume (L).

Total suspended solids (TSS) were determined for all runoff water samples by vacuum filtering (0.45 μm) 50 mL of well-mixed runoff water sample and drying the vacuum filter cup and filter paper at 95°C. Runoff TSS load (mg) was calculated by multiplying TSS (mg L<sup>-1</sup>) by runoff volume (L) for all runoff water samples.

### Statistical Analysis

Analysis of variance (ANOVA) was performed using PROC GLM to determine significant treatment effects within soils (SAS Institute, 2001). When significance was indicated, means were separated by a Fisher's Least Significant Difference procedure using a 0.05 significance level. For comparisons between soils, treatments were classified into four ordinal groups (treatment categories) since the actual treatment level varied from soil to soil. The simple effects of soil given treatment category were assessed with a SLICE option in an LSMEANS statement. Differences in soils given treatment category were further assessed with pairwise *t* test from a DIFF option (at a 0.05 significance level) if the simple effect from the slice was significant ( $p < 0.05$ ).

Separate simple linear regressions of DRP on M3P, WSP,  $P_{\text{sat}}$ ,  $\text{PSI}_{\text{ox}}$ , and  $\text{PSI}_{\text{WSP}}$  were performed controlling for soil in PROC GLM. Soil was added into the model as a class variable, and soil by independent variable interaction included to assess whether the slopes associated with the three soils differed. A SOLUTION option in the MODEL statement was used to obtain estimates of the slope to compare their values. Other relationships were evaluated using PROC CORR.

## RESULTS AND DISCUSSION

### Soil Characteristics

Soil pH of the study soils ranged from 5.4 to 7.6, clay content from 110 to 340 g kg<sup>-1</sup>, and organic matter from 18.0 to 24.0 g kg<sup>-1</sup> (Table 1). The P sorption data were satisfactorily described by the linearized Langmuir equation with correlation coefficients ranging from 0.96 to 0.99. Phosphorus sorption maximum ( $S_{\text{max}}$ ) estimated by Langmuir adsorption isotherms ranged from 189 to 312 mg P kg<sup>-1</sup> soil (Table 1). Overall M3P and WSP increased with increased P addition and spiking of soils resulted in a wide range of water-soluble P (3.15–230 mg kg<sup>-1</sup>) and M3P (27.8–925 mg kg<sup>-1</sup>) (Table 2). Treatment of soils resulted in similar levels of M3P and WSP ( $p > 0.05$ ) in the different soil series despite differences in pH and clay content among them (Table 2). Similar to M3P and WSP, saturation indexes increased with increased P addition within each soil series (Table 2). The  $\text{PSI}_{\text{ox}}$  ranged from 10.4 to 91.6%,  $P_{\text{sat}}$  from 8.90 to 489%, and  $\text{PSI}_{\text{WSP}}$  from 1.37 to 122% (Table 2).

### The Effect of Fertilizer Phosphorus Addition on Soil Test Phosphorus

Soil samples were collected from all treatments and analyzed periodically over a year to assess the effect of fertilizer P on soil test phosphorus (STP) over time. After fertilizer application, soil M3P increased sharply as the amount of fertilizer P increased (Table 2). The increased M3P in the Kirkland soil decreased slowly after the first 30 d with time until it reached steady state by 210 d for the 180 mg P kg<sup>-1</sup> treatment (Fig. 1).

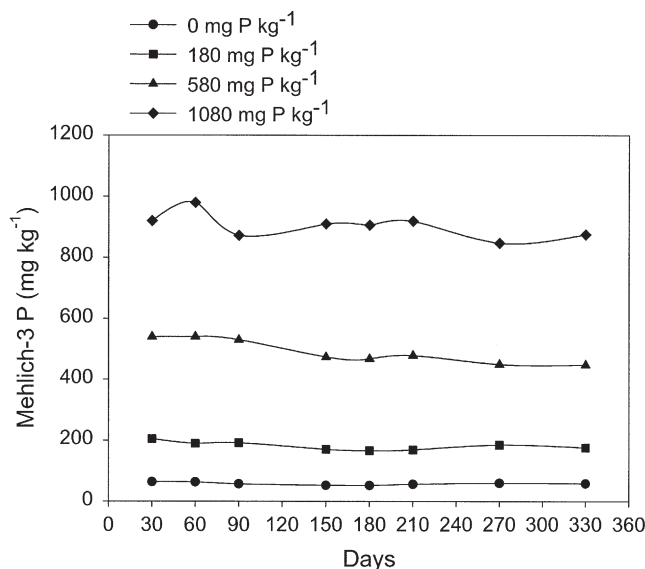


Fig. 1. Changes in Mehlich-3 P over 360 d for four fertilizer phosphorus treatments for the Kirkland soil series.

However, it appears that the 580 and 1080 mg P kg<sup>-1</sup> treatments were not at steady state at 210 d and M3P was still gradually declining after 210 d. Similar results were observed for the other two soil series. This suggests some P exists either in solution or as undissolved P fertilizer shortly after P fertilizer application. This added P is easily extractable and susceptible to dissolution and transport during a runoff event resulting in greater P runoff risk. With time, in general, added fertilizer P is gradually precipitated as Fe and Al phosphates in low pH soils or as Ca phosphates in higher pH soils. Ultimately, apatite compounds may form over great periods of time rendering soil P relatively insoluble (Pierzynski et al., 1994; Havlin et al., 1999). As runoff P is directly related to soil test P, the length of time between P application and first runoff event is very important (Sharpley et al., 1994; Daniel et al., 1994). This suggests that as soil test P was highest shortly after P fertilizer application, runoff P would also be highest immediately after fertilizer application.

Highly significant relationships ( $r^2 \geq 0.97$ ,  $p < 0.001$ ) existed between M3P and fertilizer P added for all three soils (Fig. 2A). In addition, a highly significant relationship ( $r^2 = 0.92$ ,  $p < 0.001$ ) existed between M3P and fertilizer P added for the soils combined (Fig. 2B). Simi-

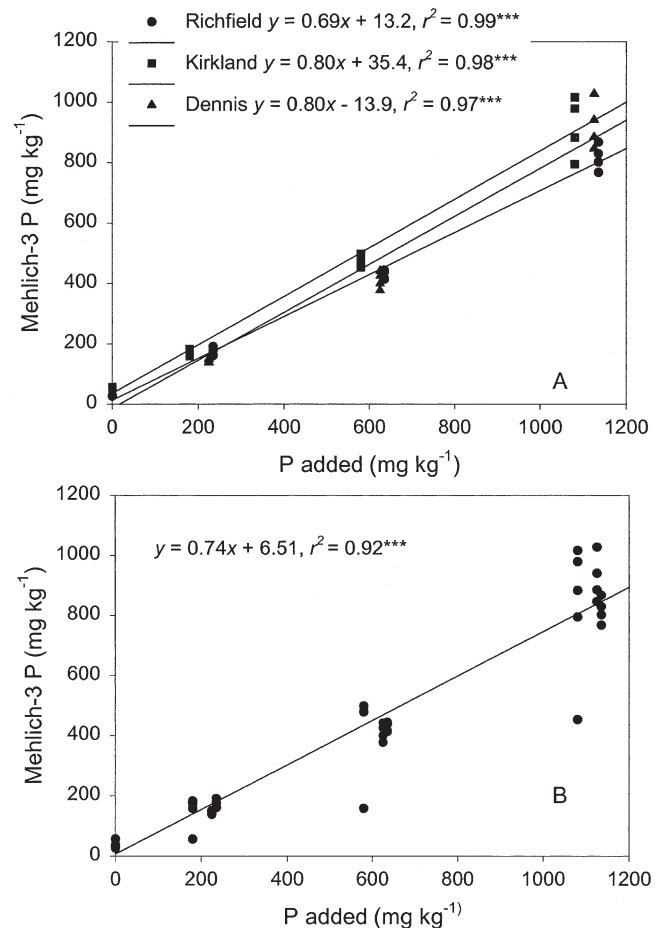


Fig. 2. The relationships between Mehlich-3 P and P added for (A) three individual study soils and (B) all soils combined. \*\*\*Significant at the 0.001 probability level.

**Table 3. Comparison of mean runoff water sample characteristics ( $n = 4$ ) within the study soils.**

Soil series	P added	Volume	Total suspended solids	Dissolved reactive P	Particulate P	Total P
	mg kg <sup>-1</sup>	L	g L <sup>-1</sup>	mg L <sup>-1</sup>		
Richfield	0	13.8a†	5.66a	0.11a	1.84a	1.95a
	235	14.8a	3.30a	0.72b	2.49ab	3.21a
	635	14.2a	5.62a	1.44c	4.54bc	5.98b
	1135	13.8a	2.67a	3.80d	5.88c	9.68c
Dennis	0	8.10a	3.30a	0.12a	0.90a	1.02a
	225	13.4a	2.51a	0.40b	1.83a	2.23b
	625	11.2a	3.13a	0.73c	3.33b	4.06c
	1125	11.9a	2.73a	1.92d	7.37c	9.29d
Kirkland	0	13.9a	5.73a	0.13a	2.12a	2.25a
	180	16.8a	3.91a	0.35a	2.49a	2.84a
	580	14.9a	6.50a	1.43b	8.51b	9.93b
	1080	14.7a	5.82a	2.30c	11.5c	13.8c

† Mean values with the same letter within a soil are not statistically different at an alpha level of 0.05.

larly, DeLaune et al. (2004) found a strong positive linear relationship existed between M3P and P added as triple super phosphate (range of 0.0–1344 mg P kg<sup>-1</sup>) for a Captina silt loam soil. Slopes for the relationships in our study ranged from 0.69 to 0.80 and are similar to the slope reported by DeLaune et al. (2004). The slope reported by DeLaune et al. (2004) for this relationship was 0.26 mg M3P kg<sup>-1</sup> per kg P ha<sup>-1</sup> added, which is equivalent to a slope of 0.59 when the P added is expressed on a mg P kg<sup>-1</sup> basis.

Highly significant relationships ( $p < 0.001$ ) also existed between WSP and P added for each soil with correlation coefficients ranging from 0.86 to 0.96 and slopes ranging from 0.13 to 0.20 (data not shown). Combination of soils resulted in a highly significant relationship between WSP and P added ( $r^2 = 0.87$ ,  $p < 0.001$ ) (data not shown).

Based on the changes of M3P averaged over all three soils one year after P fertilizer addition, it was determined that soil M3P would be raised 1 mg kg<sup>-1</sup> by the addition of 1.35 mg kg<sup>-1</sup> fertilizer P (soils combined) or a fertilizer P to M3P ratio of 1.35:1. Specifically, the Kirkland and Dennis series had the same results requiring a ratio of 1.25 while the Richfield series required 1.45:1. From a long-term soil fertility field study, Johnson et al. (1998) found that the addition of as much as 6 mg kg<sup>-1</sup> fertilizer P is required to raise soil M3P 1 mg kg<sup>-1</sup>. It is difficult to compare the results of this study with the field data since the field study lasted for more than 25 yr and field P loss beyond crop removal

was not included. Our study collected data in a controlled environment over a period of one year and removed many environmental factors that would influence P dynamics such as microorganisms, plants, organic matter reactions, etc. As such, our estimation that soil M3P would be raised 1 mg kg<sup>-1</sup> by the addition of 1.35 mg kg<sup>-1</sup> fertilizer is probably an underestimation of the amount of fertilizer that would be required in a natural field system where these factors are present. Therefore, the estimation made by Johnson et al. (1998) is probably a more accurate representation of the amount of fertilizer needed in a field situation to raise soil M3P by 1 mg kg<sup>-1</sup>. Producers and researchers would be able to predict STP if the relationship between STP and P addition can be established, but short-term indoor controlled variable experiments may result in different relationships from those derived from long-term field data and care should be exercised in extrapolating these results to field situations.

### Runoff Sample Characteristics

Runoff volumes did not vary ( $p > 0.05$ ) within treatments for each individual soil series (Table 3). Similarly, runoff volumes were similar ( $p > 0.05$ ) between soils for most treatments (Table 4). Total suspended solids were statistically equivalent ( $p > 0.05$ ) within treatments for each individual soil series (Table 3) as well as between soils (Table 4). Conversely, DRP varied within treatments ( $p < 0.05$ ) for each individual soil series and

**Table 4. Comparisons of mean runoff sample characteristics ( $n = 4$ ) between the study soils.**

Soil series	Treatment	P added	Volume	Total suspended solids	Dissolved reactive P	Particulate P	Total P
		mg kg <sup>-1</sup>	L	g L <sup>-1</sup>	mg L <sup>-1</sup>		
Richfield	1	0	13.8a†	5.66a	0.11a	1.84a	1.95a
Dennis	1	0	8.10b	3.30a	0.12a	0.90a	1.02a
Kirkland	1	0	13.9a	5.73a	0.14a	2.12a	2.25a
Richfield	2	235	14.8a	3.30a	0.73a	2.49a	3.21a
Dennis	2	225	13.4a	2.51a	0.40b	1.83a	2.24a
Kirkland	2	180	16.8a	3.91a	0.34b	2.49a	2.84a
Richfield	3	635	14.2a	5.62a	1.44a	4.54b	5.98b
Dennis	3	625	11.2a	3.13a	0.73b	3.34b	4.06b
Kirkland	3	580	14.9a	6.50a	1.43a	8.51a	9.93a
Richfield	4	1135	13.8a	2.68a	3.80a	5.88b	9.68b
Dennis	4	1125	11.9a	2.74a	1.92c	7.37b	9.29b
Kirkland	4	1080	14.7a	5.82a	2.27b	11.5a	13.8a

† Mean values with the same letter within a treatment are not statistically different at an alpha level of 0.05.

increased with increasing P addition (Table 3). The DRP also varied ( $p < 0.05$ ) between soils for most treatments with the exception of the control plots, which showed no difference between soils (Table 4). Similar to DRP, particulate P and total P increased with increasing P addition within treatments for each individual soil series (Table 3). No differences were observed ( $p > 0.05$ ) between soils for levels of particulate P at Treatments 1 and 2 (Table 4). At higher treatments (i.e., Treatments 3 and 4), particulate P was greater for the Kirkland soil ( $p < 0.05$ ) as compared to the Richfield and Dennis soils, which were statistically equivalent ( $p > 0.05$ ) (Table 4). Similar patterns were observed between soils for total P.

**Relationships between Phosphorus Extractions and Saturation Indexes**

Soil samples were collected immediately before rainfall simulation and analyzed for M3P, WSP, PSI<sub>ox</sub>, P<sub>sat</sub>, and PSI<sub>WSP</sub> (Table 2). Extractable P values (M3P or WSP) and P saturation indexes (PSI<sub>ox</sub>, P<sub>sat</sub>, or PSI<sub>WSP</sub>) were well-correlated among themselves ( $r^2 > 0.95$ ,  $p < 0.001$ ) for the individual study soils (Table 5). For all soils combined M3P was highly related ( $r^2 = 0.92$ ,  $p < 0.001$ ) to WSP. Our results agree well with those of several other researchers who have reported highly significant relationships between WSP and M3P (McDowell and Sharpley, 2001; Burt et al., 2002; Sims et al., 2002; Fuhrman et al., 2005). Additionally, M3P was highly correlated with PSI<sub>ox</sub> ( $r^2 = 0.85$ ,  $p < 0.001$ ), P<sub>sat</sub> ( $r^2 = 0.92$ ,  $p < 0.001$ ), and PSI<sub>WSP</sub> ( $r^2 = 0.83$ ,  $p < 0.001$ ) (Table 5). Similarly, WSP was highly related to PSI<sub>ox</sub> ( $r^2 = 0.95$ ,  $p < 0.001$ ), P<sub>sat</sub> ( $r^2 = 0.75$ ,  $p < 0.001$ ), and PSI<sub>WSP</sub> ( $r^2 = 0.92$ ,  $p < 0.001$ ). Our results for PSI<sub>ox</sub> are similar to those reported by Sims et al. (2002) who found that PSI<sub>ox</sub> was highly correlated with both WSP and M3P. A highly significant relationship was found be-

tween PSI<sub>ox</sub> and PSI<sub>WSP</sub> ( $r^2 = 0.89$ ,  $p < 0.001$ ) while a weaker relationship was established ( $r^2 = 0.64$ ,  $p < 0.001$ ) between PSI<sub>ox</sub> and P<sub>sat</sub>. The results of this study are similar to those reported by Zhang et al. (2005) who found significant relationships between PSI<sub>ox</sub> and P<sub>sat</sub>. In this study, P<sub>sat</sub> was highly correlated with PSI<sub>WSP</sub> ( $r^2 = 0.71$ ,  $p < 0.001$ ) (Table 5).

**Relationships between Runoff Phosphorus and Soil Phosphorus**

Total P concentrations in runoff ranged from 1.0 to 14 mg L<sup>-1</sup> for all treatments (Table 4). Total runoff P was highly correlated ( $p < 0.001$ ) with WSP ( $r^2 = 0.77-0.85$ ), M3P ( $r^2 = 0.81-0.92$ ), PSI<sub>ox</sub> ( $r^2 = 0.71-0.85$ ), P<sub>sat</sub> ( $r^2 = 0.81-0.92$ ), and PSI<sub>WSP</sub> ( $r^2 = 0.77-0.85$ ) for the individual soil series (data not shown). Combination of soils resulted in slightly weaker but significant relationships ( $p < 0.01$ ) between extractable P and saturation indexes and total runoff P. Correlations of extractable P and saturation indexes with total runoff P for combined soils were: WSP ( $r^2 = 0.56$ ), M3P ( $r^2 = 0.75$ ), PSI<sub>ox</sub> ( $r^2 = 0.49$ ), P<sub>sat</sub> ( $r^2 = 0.62$ ), and PSI<sub>WSP</sub> ( $r^2 = 0.45$ ) (data not shown). However, particulate phosphorus (PP) was not well correlated ( $p > 0.05$ ) with soil M3P, WSP, PSI<sub>ox</sub>, P<sub>sat</sub>, or PSI<sub>Smax</sub>. Particulate P constituted most of TP (61-94%) for all treatments although the percentage of PP decreased with an increase in soil P (Table 3). Sharpley et al. (1994) reported that PP composed 75 to 95% of runoff total P while Fang et al. (2002) reported that PP contributed from 59 to 98% of total runoff P for unvegetated packed boxes.

Runoff DRP ranged from 0.11 to 3.8 mg L<sup>-1</sup> for all treatments (Table 3) and was highly correlated ( $p < 0.001$ ) with M3P for the Richfield ( $r^2 = 0.95$ ), Kirkland ( $r^2 = 0.92$ ), and Dennis ( $r^2 = 0.95$ ) soil series (Fig. 3A). Our results for individual soil series are similar to those

**Table 5. Correlation matrix for phosphorus extraction methods and phosphorus saturation indexes for the study soils.**

Soil		M3P†	WSP‡	PSI <sub>ox</sub> §	P <sub>sat</sub>	PSI <sub>WSP</sub> #
Richfield	M3P	1.00	0.99***	0.99***	0.99***	0.99***
	WSP		1.00	0.96***	0.99***	0.99***
	PSI <sub>ox</sub>			1.00	0.99***	0.97***
	P <sub>sat</sub>				1.00	0.99***
	PSI <sub>WSP</sub>					1.00
Dennis	M3P	1.00	0.98***	0.99***	0.99***	0.97***
	WSP		1.00	0.97***	0.95**	0.99***
	PSI <sub>ox</sub>			1.00	0.99***	0.98***
	P <sub>sat</sub>				1.00	0.95***
	PSI <sub>WSP</sub>					1.00
Kirkland	M3P	1.00	0.99***	0.98***	0.99***	0.99***
	WSP		1.00	0.97***	0.99***	0.99***
	PSI <sub>ox</sub>			1.00	0.96***	0.97***
	P <sub>sat</sub>				1.00	0.99***
	PSI <sub>WSP</sub>					1.00
Combined soils	M3P	1.00	0.92***	0.85***	0.92***	0.83***
	WSP		1.00	0.95***	0.75***	0.92***
	PSI <sub>ox</sub>			1.00	0.64***	0.89***
	P <sub>sat</sub>				1.00	0.71***
	PSI <sub>WSP</sub>					1.00

\*\*\* Significant at the 0.001 probability level.

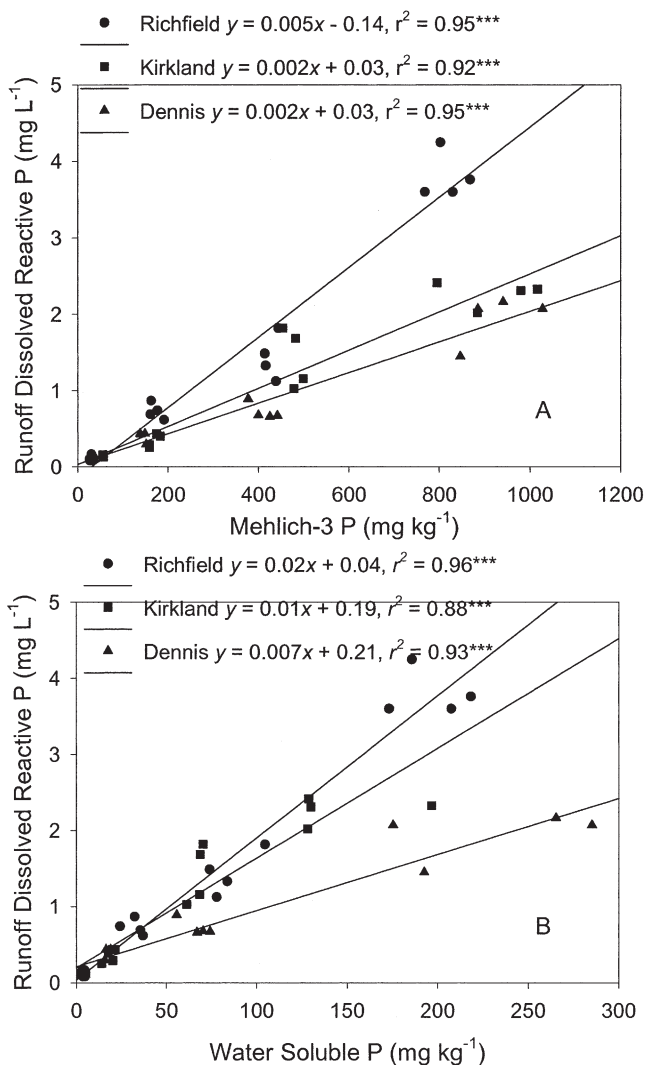
† Mehlich 3-extractable phosphorus.

‡ Water-soluble phosphorus.

§ Phosphorus saturation index calculated from acid ammonium oxalate data (oxalate P/oxalate Al + oxalate Fe).

|| Phosphorus saturation index calculated from M3P and P sorption maxima (M3P/S<sub>max</sub>).

# Phosphorus saturation index calculated from water-soluble P and P sorption maxima (WSP/S<sub>max</sub>).



**Fig. 3. The relationships between runoff dissolved reactive P and (A) Mehlich-3 P and (B) water-soluble P for the three study soils. \*\*\*Significant at the 0.001 probability level.**

of other researchers who have reported highly significant relationships between runoff DRP and M3P for individual soil series (Sharpley, 1995; Pote et al., 1996, 1999; Torbert et al., 2002; DeLaune et al., 2004; Kleinman et al., 2004). Slopes for the regressions between runoff DRP and soil P concentrations are referred to as extraction coefficients and are typically used as model inputs for P transport models and P site assessment indices (Sharpley et al., 2002; Kleinman et al., 2004). Extraction coefficients for our study ranged from 0.002 to 0.005. The extraction coefficients for our study are similar to those reported by Sharpley (1995) who reported extraction coefficients ranged from 0.0016 to 0.0072 for unvegetated packed boxes of 10 Oklahoma soils. Our results are consistent with those of Fang et al. (2002) whose extraction coefficient was 0.006 for a study involving unvegetated packed boxes of 10 alkaline soils.

Statistical analysis showed that the slopes of regressions for the Dennis and Kirkland soil series were statistically equivalent ( $p > 0.05$ ) but that the slope of the regression for the Richfield was statistically different

( $p < 0.05$ ) than the other two soils. Our results are consistent with other researchers who have found the slope of the relationship between DRP and M3P differed among soils (Sharpley, 1995; Pote et al., 1999; Cox and Hendricks, 2000; Torbert et al., 2002).

Pote et al. (1996) reported a highly significant relationship between DRP and WSP for a Captina silt loam soil in Arkansas that received P inputs as swine and poultry manure. Similarly in our study, DRP was highly related to WSP ( $p < 0.001$ ) for the individual soil series (Fig. 3B). Correlation coefficients for the individual soil series were: Richfield ( $r^2 = 0.96$ ), Kirkland ( $r^2 = 0.88$ ), and Dennis ( $r^2 = 0.93$ ) (Fig. 3B). Our results are similar to those of McDowell and Sharpley (2001) and Fang et al. (2002) who found highly significant relationships between DRP and WSP. Statistical analysis revealed that each soil series expressed a significantly different relationship ( $p < 0.05$ ) between DRP and WSP. These findings are consistent with those found by Pote et al. (1999) among three Ultisols and other researchers who have studied the relationship between DRP and WSP (Sharpley, 1995; Cox and Hendricks, 2000; Torbert et al., 2002).

### Relationships between Normalized Runoff Phosphorus and Soil Phosphorus

In an attempt to develop one regression equation to describe the relationship between runoff DRP and soil P for a combination of soils, several researchers have normalized DRP and then examined the relationships between DRP and soil P. Pote et al. (1999) normalized runoff DRP concentrations for three Ultisols to correct for observed DRP–soil P relationship differences among soils. In their study, Pote et al. (1999) found that by normalizing runoff DRP concentration one regression equation could be used to adequately describe the relationships between runoff DRP and water-soluble P. Kleinman et al. (2004) normalized DRP by dividing it by rainfall, runoff depth, area, and various combinations of these factors. Their study found that normalizing DRP did not significantly improve the relationships between DRP and M3P. Similarly to Kleinman et al. (2004), normalization of DRP by rainfall, runoff depth, area, and various combinations of these factors did not significantly improve the relationship between DRP and M3P in our study (Table 6). Unlike the study by Pote et al. (1999), normalization of DRP did not improve the relationship between DRP and water-soluble P for our study (Table 6). As the Pote et al. (1999) study was performed on three Ultisols in a field situation, the hydrological properties of the soils evaluated were probably not impacted to the extent of the soils in this study. The soils in this study were removed from the field and sieved. Both of these actions may have influenced the physical properties (e.g., bulk density, pore volume, etc.) of the soils. In addition, this study worked with a much wider range of M3P and WSP and the differences between the regression lines seem to be amplified at high levels of M3P and WSP. Lastly, all soil surfaces in this study had no surface cover while the sites evaluated by

**Table 6. Regression equations and regression coefficients ( $r^2$ ) for the relationships between dissolved reactive phosphorus (DRP) normalized by rainfall, runoff depth, and area of plot and Mehlich 3-extractable or water-soluble phosphorus.**

DRP in runoff divided by	Regression equation	$r^2$
<b>Mehlich-3 P</b>		
Rainfall (cm)	$y = 0.0069x + 0.014$	0.77***
Runoff (cm)	$y = 0.00081x + 0.0071$	0.77***
Area (cm <sup>2</sup> )	$y = 0.00000068x + 0.0000063$	0.75***
Rainfall (cm) × runoff (cm)	$y = 0.00020x + 0.0039$	0.79***
Rainfall (cm) × area (cm <sup>2</sup> )	$y = 0.00000016 + 0.0000033$	0.77***
Runoff (cm) × area (cm <sup>2</sup> )	$y = 0.000000019x + 0.0000017$	0.77***
Rainfall (cm) × runoff (cm) × area (cm <sup>2</sup> )	$y = 0.00000000046x + 0.00000093$	0.79***
<b>Water-soluble P</b>		
Rainfall (cm)	$y = 0.0029x + 0.067$	0.75***
Runoff (cm)	$y = 0.0035x + 0.060$	0.80***
Area (cm <sup>2</sup> )	$y = 0.00000029x + 0.000056$	0.74***
Rainfall (cm) × runoff (cm)	$y = 0.00085x + 0.017$	0.81***
Rainfall (cm) × area (cm <sup>2</sup> )	$0.00000069x + 0.0000016$	0.75***
Runoff (cm) × area (cm <sup>2</sup> )	$0.00000083x + 0.000014$	0.80***
Rainfall (cm) × runoff (cm) × area (cm <sup>2</sup> )	$y = 0.00000020x + 0.00000040$	0.81***

\*\*\* Significant at the 0.001 probability level.

Pote et al. (1999) were under well-established tall fescue (*Festuca arundinacea* Schreb).

### Relationships between Runoff Phosphorus and Phosphorus Saturation Indexes

Highly significant relationships were observed between DRP and  $PSI_{ox}$  for the individual soil series ( $r^2 > 0.89$ ,  $p < 0.001$ ) (Fig. 4A). The results of our study are similar to those of Pote et al. (1996) who reported highly significant relationships between DRP and  $PSI_{ox}$  for a Captina silt loam soil. Significant relationships existed ( $p < 0.001$ ) between DRP and  $P_{sat}$  for the individual soil series with regression coefficients ranging from 0.92 to 0.95 (Fig. 4B). Our results are similar to those of Sharpley (1995) who reported significant relationships between DRP and  $P_{sat}$  for 10 different soils. Significant relationships ( $r^2 > 0.88$ ,  $p < 0.001$ ) were observed between DRP and  $PSI_{WSP}$  for the individual soil series (Fig. 4C). Statistical analysis indicated that there were significant differences ( $p < 0.05$ ) among the slopes of the regressions for the DRP- $PSI_{ox}$ , DRP- $PSI_{WSP}$ , and DRP- $P_{sat}$  relationships. However, the slopes of the regressions for the Kirkland and Richfield soils were statistically equivalent ( $p > 0.05$ ) while the slope of the regression for the Dennis soil was statistically different ( $p < 0.05$ ) than the other two soils for the DRP- $PSI_{ox}$  relationship. The results of our study contrast with those of Sharpley (1995) who found that slopes of the DRP- $P_{sat}$  regression were similar for 10 different soils.

### Relationships between Phosphorus Load and Soil Phosphorus

The DRP load was highly related to M3P ( $p < 0.0001$ ) for the Richfield ( $r^2 = 0.90$ ), Kirkland ( $r^2 = 0.91$ ), and Dennis ( $r^2 = 0.90$ ) soil series (Fig. 5A). Highly significant relationships ( $r^2 > 0.78$ ,  $p < 0.001$ ) were observed between DRP load and water-soluble P for the individual study soils (Fig. 5B). Our results for individual soils are similar to those of Pote et al. (1999) who found that DRP load in runoff was highly correlated with water-extractable P for three different Ultisols.

## CONCLUSIONS

The addition of fertilizer P to the three soils in this experiment increased M3P and WSP. Initially M3P increased rapidly during first 30 d then decreased slowly with time until it reached steady state by 210 d for the 180 mg P kg<sup>-1</sup> treatment. However, the 580 and 1080 mg P kg<sup>-1</sup> treatments were not at steady state at 210 d and M3P was gradually declining after 210 d. This information may be useful to predict soil test P changes due to fertilization.

Highly significant relationships existed between M3P and fertilizer P added as well as between WSP and fertilizer P added. It was found the addition of about 1.35 mg fertilizer P for each kg soil raised M3P one unit (mg kg<sup>-1</sup>) one year after P addition. As this was an indoor experiment, many environmental variables were controlled thusly providing an accurate assessment of the actual amount of fertilizer P required to raise soil M3P by one unit. This information may also prove useful for future controlled environment experiments involving the addition of fertilizer P to achieve a predetermined soil M3P level, and to estimate time required to reach a critical M3P level for farmers. However, short-term indoor controlled variable experiments may result in different relationships from those derived from long-term field studies and care should be exercised in extrapolating these results to field situations.

Runoff volumes did not vary within treatment for individual soil series nor among soils. Similarly, there was no difference between total suspended solids within treatments for individual soils and no difference between soils for the different treatments. However, DRP increased with increasing P addition within treatments for the soils. The DRP also varied between soils and DRP for Kirkland and Richfield was greater than DRP for the Dennis soil.

Highly significant relationships were found between DRP and M3P and between DRP and WSP for the individual soils. The difference between the slopes of the regressions for both the DRP-M3P relationship and DRP-WSP relationship for different soils indicates the relationships are probably soil specific. Normalization

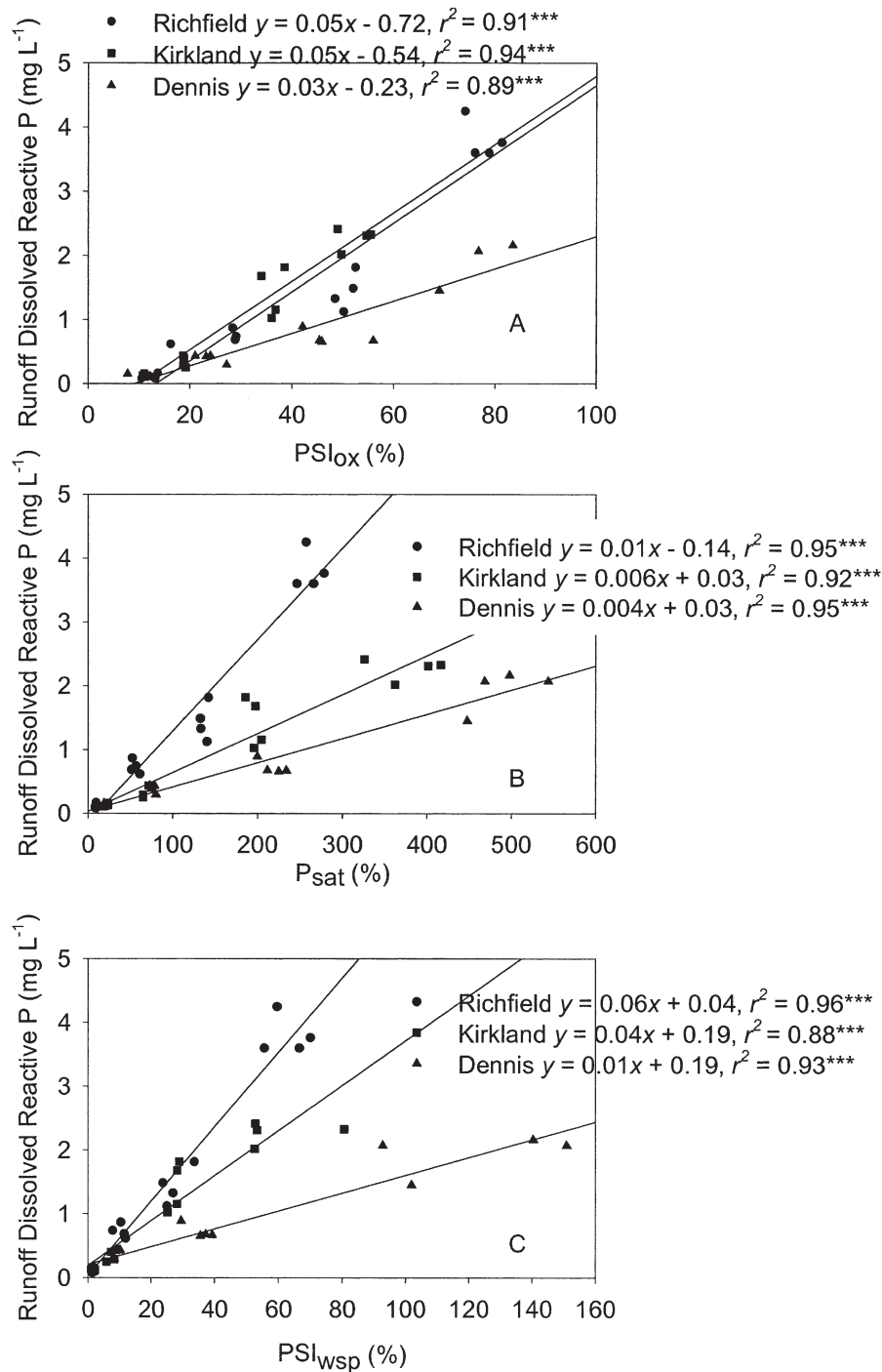
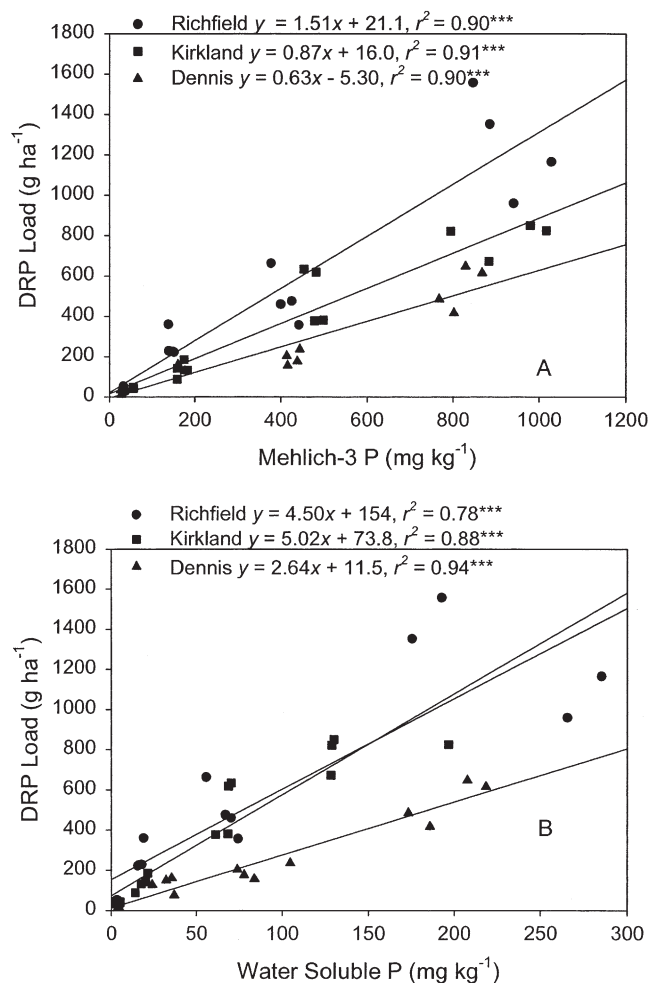


Fig. 4. The relationships between runoff dissolved reactive P and (A) phosphorus saturation index calculated with acid ammonium oxalate-extractable data (PSI<sub>ox</sub>), (B) a phosphorus saturation index calculated with Mehlich-3 P and  $S_{max}$  (P<sub>sat</sub>), and (C) a phosphorus saturation index calculated with water-soluble P and  $S_{max}$  (PSI<sub>wsp</sub>) for the three study soils. \*\*\*Significant at the 0.001 probability level.

of data did not significantly improve the relationships between DRP and M3P or between DRP and WSP.

Highly significant relationships were found between DRP and P<sub>sat</sub> and between DRP and PSI<sub>wsp</sub> for individual soil series. Similarly, a highly significant relationship was observed between DRP and PSI<sub>ox</sub> for individual soil series. Statistical analyses indicated significant differences in the slopes ( $p < 0.05$ ) for the DRP–P<sub>sat</sub> relationship and the DRP–PSI<sub>wsp</sub> relationship. The slopes of

the regressions for the Kirkland and Richfield soil series were statistically equivalent ( $p > 0.05$ ) while the slope of the regression for the Dennis was statistically different ( $p < 0.05$ ) than the other two soils for the DRP–PSI<sub>ox</sub> relationship indicating that PSI<sub>ox</sub> may be a more appropriate saturation index. Highly significant relationships existed between DRP load and M3P for the individual soil series. Similar relationships were found between DRP load and WSP for the individual soil series. Sum-



**Fig. 5. The relationships between phosphorus load and (A) Mehlich-3 P and (B) water-soluble P for the three study soils. \*\*\*Significant at the 0.001 probability level.**

marizing, statistical analyses revealed significant differences ( $p < 0.05$ ) for the slopes of the regressions for the DRP–M3P, DRP–WSP, DRP–PSI<sub>ox</sub>, DRP–PSI<sub>wsp</sub>, and DRP–P<sub>sat</sub> relationships indicating the relationships will probably have to be soil specific to be useful in management decisions.

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