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Relating Soil Phosphorus to Dissolved Phosphorus in Runoff: A Single Extraction Coefficient for Water Quality Modeling

P. A. Vadas,* P. J. A. Kleinman, A. N. Sharpley, and B. L. Turner

ABSTRACT

Phosphorus transport from agricultural soils contributes to eutrophication of fresh waters. Computer modeling can help identify agricultural areas with high potential P transport. Most models use a constant extraction coefficient (i.e., the slope of the linear regression between filterable reactive phosphorus [FRP] in runoff and soil P) to predict dissolved P release from soil to runoff, yet it is unclear how variations in soil properties, management practices, or hydrology affect extraction coefficients. We investigated published data from 17 studies that determined extraction coefficients using Mehlich-3 or Bray-1 soil P (mg kg^{-1}), water-extractable soil P (mg kg^{-1}), or soil P sorption saturation (%) as determined by ammonium oxalate extraction. Studies represented 31 soils with a variety of management conditions. Extraction coefficients from Mehlich-3 or Bray-1 soil P were not significantly different for 26 of 31 soils, with values ranging from 1.2 to 3.0. Extraction coefficients from water-extractable soil P were not significantly different for 17 of 20 soils, with values ranging from 6.0 to 18.3. The relationship between soil P sorption saturation and runoff FRP ($\mu g\ L^{-1}$) was the same for all 10 soils investigated, exhibiting a split-line relationship where runoff FRP rapidly increased at P sorption saturation values greater than 12.5%. Overall, a single extraction coefficient (2.0 for Mehlich-3 P data, 11.2 for water-extractable P data, and a split-line relationship for P sorption saturation data) could be used in water quality models to approximate dissolved P release from soil to runoff for the majority of soil, hydrologic, or management conditions. A test for soil P sorption saturation may provide the most universal approximation, but only for noncalcareous soils.

Transfer of P from agricultural soils to freshwater bodies contributes to their accelerated eutrophication, which limits water use for drinking, recreation, and industry (Bennett et al., 2001; Sharpley et al., 1999). One approach to address this P pollution has been to identify areas in agricultural watersheds with high potential for P export, quantify the P export, and assess the ability of management practices to minimize the export (Coale et al., 2002). During the last decade, understanding of the sources and transport pathways of pollutant P transfer has improved markedly (Gburek et al., 2000; Sims et al., 2000). However, this improved understanding is not necessarily reflected in widely used computer models (Sharpley et al., 2002), despite their critical role in identifying areas in watersheds with a high potential for P export.

All water quality models concerned with P transport simulate desorption of P from soil to runoff water. Most models estimate dissolved inorganic P concentrations in runoff as the product of the soil P concentration and an extraction coefficient, which is typically a constant for all soil, runoff, and management conditions (National Research Council, 2000; Sharpley et al., 2002). Because even small amounts of P transfer can impair the quality of receiving waters (Carpenter et al., 1998; Sharpley and Rekolainen, 1997), determining accurate values for extraction coefficients is critical for reliable model predictions.

Linear relationships between concentrations of soil P, as estimated by an appropriate chemical extraction, and runoff filterable reactive phosphorus [FRP; P passing through a 0.45-μm filter and measured by the Murphy and Riley (1962) method] are commonly reported. Extraction coefficients, determined as the slope of the linear regression between soil P and runoff FRP, vary among studies (Sharpley et al., 1996). Variability has been attributed to differences in soil properties, such as clay content (Cox and Hendricks, 2000), P adsorption capacity (Sharpley, 1995), and $CaCO_3$ content (Torbert et al., 2002), differences in runoff conditions, such as runoff quantity (Pote et al., 1999b; Andraski and Bundy, 2003) and antecedent soil moisture (Pote et al., 1999a), or differences in management practices, such as pasture and tilled soils (Sharpley et al., 2002). There has been little effort to determine if such attributions apply across a large set of data from several studies. Such comparison would elucidate whether accounting for specific soil properties, runoff conditions, or management practices can improve the estimation of extraction coefficients. Our objectives were to review the literature for studies relating soil P to runoff FRP and to determine if there are consistent trends in reported relationships and if these trends could be attributed to differences in soil type, runoff hydrology, management practices, or experimental methodology.

MATERIALS AND METHODS

Literature Review

We reviewed the literature for studies relating concentrations of soil P and runoff FRP (Table 1). Within studies, extraction coefficients, determined as the slope of the linear regression between soil P and runoff FRP, varied depending on the extractant used to estimate soil P. Strong chemical extractants, such as Mehlich 3, extract more P than weaker extractants, such as water. If Mehlich-3 and water-extractable soil P data are regressed against the same runoff FRP data, the Mehlich-3 extraction coefficient is less than the water extraction coefficient. To compare extraction coefficients across studies, we used data that had either Mehlich 3 (0.2 *M* CH_3COOH + 0.25 *M* NH_4NO_3 + 0.015 *M* NH_4F + 0.013 *M* HNO_3 + 0.001 *M*

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Abbreviations: FRP, filtered reactive phosphorus.

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EDTA; Mehlich, 1984) or Bray 1 (0.03 *M* NH_4F + 0.025 *M* HCl; Bray and Kurtz, 1945) as the soil P extractant, as these solutions extract about the same amount of P from soils (Kleinman et al., 2001; Burt et al., 2002). This allowed us to compare the maximum number of studies (Table 1).

The Mehlich-3 and Bray-1 extractants were developed as agronomic tests to determine crop response to P fertilization. Because they were not developed to predict dissolved P in runoff, some researchers have suggested that other soil tests may either better mimic the interaction between soil and runoff or better represent the likelihood of P release from soil to runoff (Sharpley, 1995; Pote et al., 1999b; Hesketh and Brookes, 2000; McDowell and Sharpley, 2001b). These "environmental" tests would therefore better predict dissolved P in runoff. Such tests include extractions with deionized water, a weak salt solution such as 0.01 *M* $CaCl_2$, or iron oxide–impregnated filter paper, and a test for soil P sorption saturation.

We conducted a second literature review for studies that determined extraction coefficients using environmental soil P tests. The most data were available for either a water extraction or test for soil P sorption saturation, but methods varied widely across studies, often preventing direct comparison of data. This demonstrates the need for consistent experimental protocols if data are to be useful to wide audiences. Ultimately, we used data from water extractions conducted for 60 min at a water to soil ratio of 25, as this method gave us the most studies to compare. We also used data from P sorption saturation tests conducted by extraction with ammonium oxalate [0.2 *M* $(NH4)_2C_2O_4$; McKeague and Day, 1966] with P sorption saturation calculated as extractable P (mmol kg^{-1}) divided by the sum of extractable Fe and Al (mmol kg^{-1}) and multiplied by 100 (Schoumans, 2000).

All studies used similar rainfall simulation, runoff collection, and analytical methods to determine runoff FRP. Rainfall simulators had either veejet, teejet, or oscillating nozzles set at about 3 m above the soil surface. Rainfall was applied at rates ranging from 50 to 100 mm h^{-1} for times ranging from 15 to 160 min, which represented storm return periods ranging from 5 to 50 yr. Runoff was collected for either 15, 30, or 60 min, and a sample of runoff representing the entire runoff period was filtered through 0.45-μm filters and analyzed for FRP (Murphy and Riley, 1962).

Soil physicochemical properties and management conditions during rainfall simulations varied across studies. Some studies used soil boxes ranging in size from 15 × 60 to 120 × 150 cm and packed with either ground and sieved soil or soil as collected intact from the field. Packed soil had a bulk density of 1.2 to 1.4 g cm^{-3}, and boxes were set at a slope ranging from 2.4 to 5% during rainfall simulations. Other studies conducted simulated rainfalls on field plots ranging in size from 0.9 × 0.9 to 1.5 × 6.0 m, ranging in slope from 2 to 25%, and having different management conditions, such as pasture or cropped, with either tillage or no-till.

Torbert et al. (2002) showed that soil sampling depth has a significant effect on extraction coefficients when there is vertical stratification of soil P concentrations. In soils with infrequent or no tillage and regular applications of P in manure or fertilizer, soil P will be greatest at the soil surface and will decrease with depth (Kingery et al., 1994; Sims et al., 1998). Therefore, more P can be extracted from a soil sample taken from a depth of 0 to 2 cm than from 0 to 15 cm. When these variable soil P data are regressed against the same runoff FRP data, the resulting extraction coefficient for 0- to 2-cm samples is less. We compared extraction coefficients only when soil samples clearly represented that soil interacting with runoff during rainfall simulations. This meant using data from soil samples taken at the time of rainfall simulations and from shallow

Table 1. Extraction coefficients relating soil P (*x* variable, mg kg^{-1}) to runoff filterable reactive phosphorus (FRP; *y* variable, μg L^{-1}) from a review of literature.

Reference	State	Soil(s)	Soil pH	Soil clay	Soil $CaCO_3$	Land use	Soil sample depth	Observations	Runoff FRP	Extraction coefficient			
										Bray 1	Mehlich 3	Water	DPSS†
				%	%		cm		mg L^{-1}				
Aase et al. (2001)	ID	silt loam	7.7–7.9	–	–	tilled plots	0–8	48	0–0.4	–	–	12–17	–
Andraski and Bundy (2003)	WI	silt loams, clay loam	6.5–7.5	16–38	–	cropped plots	0–2, 5, 15	126	0–1.0	2.0–13.0	1.3–3.0	5–24	1–42
Andraski et al. (2003)	WI	silt loams	6.5–7.0	16–27	–	cropped plots	0–2, 5, 15	127	0–0.3	1.9–2.6	1.7	11	20
Cox and Hendricks (2000)	NC	clay loam and loamy sand	–	5–30	–	cropped plots	0–15, 20	20	0–2.0	–	1.4–3.9	–	–
Daverede et al. (2003)	IL	silty clay loam	6.1	24.5	–	cropped plots	0–2	64	0–1.0	0.6–0.8	–	4.3	–
Fang et al. (2002)	MN	silty clay loams, clay loams, clays	5.8–8.0	33–57	1–10	soil boxes	0–5	10	0–1.0	9.8	5.8	–	–
McDowell and Sharpley (2001a)	PA	silt loams	4.7–7.2	20–40	–	soil boxes, pasture, tilled plots	0–5	88	0–1.0	–	1.7–1.9	72–83	–
Pote et al. (1996)	AR	silt loam	5.0	0.8	–	fescue plots	0–2	54	0.2–1.6	2.2	2.6	12	24
Pote et al. (1999b)	AR	silt loam and sandy loams	5.2–6.2	7–15	–	fescue plots	0–2	36	0–1.2	2.7–4.3	1.6–3.6	5–11	25–82
Pote et al. (1999a)	AR	silt loam	5.0	1.1	–	fescue plots	0–2	36	0–1.4	–	2.2–2.8	15–26	–
Schroeder et al. (2004)	GA	sandy loams	5.0–5.7	6–24	–	pasture plots	0–2, 5, 10	54	0–1.1	–	1.7–2.0	11–15	14–16
Sharpley et al. (2001)	PA	silt loams	5.7–6.8	20–40	–	pasture, tilled plots	0–5	–	–	–	2.1	–	–
Torbert et al. (2002)	TX	sandy loam, clay loam, clays	7.1–8.0	21–57	1–40	Bermuda grass plots	0–2, 5, 15	72	0–1.6	–	0.4–7.0	7–52	–
Turner et al. (2004)	ID	silt loams, fine sandy loam	7.7–8.1	10–25	2–25	tilled plots	0–3	50	0–0.7	–	1.2–2.8	2–47	–
Weld et al. (2001)	PA	silt loams	–	–	–	soil boxes	0–5	–	–	–	1.5–1.7	–	–

† Degree of soil P sorption saturation as measured with an acid ammonium oxalate extraction. DPS = 100 × P/(Fe + Al).

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depths, typically 0 to 2 or 0 to 5 cm. We also used data from deeper soil samples, typically 0 to 15 or 0 to 20 cm, when soils had been recently tilled throughout the entire sampling depth, thus diminishing any significant soil P stratification. When required data were not published in tables or figures, we obtained data directly from authors.

Many studies have demonstrated temporal trends in soil P release to water following P addition to soil. Sharpley and Ahuja (1982) added KH_2PO_4 to two soils and found that water-extractable soil P decreased over the 55-d incubation. Similar trends were observed by Indiati et al. (1999) when incubating with KH_2PO_4, and by Robinson and Sharpley (1996) when incubating with both KH_2PO_4 and poultry litter leachate. Sauer et al. (2000) and Kleinman et al. (2002) clearly showed that recent P additions to soils, whether in manure or fertilizer and whether surface-applied or incorporated, eliminate the relationship between soil P and runoff FRP. This effect decreases with time as the added P reaches a chemical equilibrium in soils. Therefore, we compared extraction coefficients only from data with no P additions to soils at least six months before rainfall simulations.

Statistical Analysis

We quantified the relationship between runoff FRP and soil P by least squares regression. The slope of the linear regression was the extraction coefficient. For the majority of studies, we determined extraction coefficients for data from a single soil type. When a study used several similar soil types to provide a range of soil test P values, we determined extraction coefficients from collective data of the several soils. Whenever we compared extraction coefficients, we conducted a statistical test for homogeneity of regression coefficients at the 5% level to determine any significant differences (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Literature Review of Studies Using the Mehlich-3 and Bray-1 Soil Tests

Comparison of Studies Using Soil Boxes

We used data from Fang et al. (2002), Kleinman and Sharpley (2003), Kleinman et al. (2002, 2004), McDowell and Sharpley (2001a), and Weld et al. (2001). All studies used ground and sieved (2 mm) soils, except for Weld et al. (2001), who collected soils intact from the field (Table 1). For the 6 studies and 10 soil types, there was no significant difference among any of the extraction coefficients (Fig. 1a), most of which ranged from only 1.5 to 2.0. The extraction coefficient for Fang et al. (2002) was greater at 5.8, but was not significantly different from other extraction coefficients. This is probably because the Fang et al. (2002) data set contained only 10 points covering a relatively narrow range of soil P (0–150 mg kg^{-1}) compared with the range of soil P for the rest of the data (0–800 mg kg^{-1}). The statistical procedure used to compare extraction coefficients may not have been sensitive to the Fang et al. (2002) data.

The reason for the greater extraction coefficient of Fang et al. (2002) was not apparent from any of the reported soil properties, runoff conditions, or experimental methods. Fang et al. (2002) also determined soil P with Bray 1 and found it was not well suited as an indicator of P availability for their soils, which were mostly calcareous. They surmised that the acid Bray-1 solution was neutralized by the soils, with CaF_2 forming, immobilizing P, and underestimating available soil P. Mallarino (1997) showed that a similar phenomenon should not occur in calcareous soils with Mehlich 3.

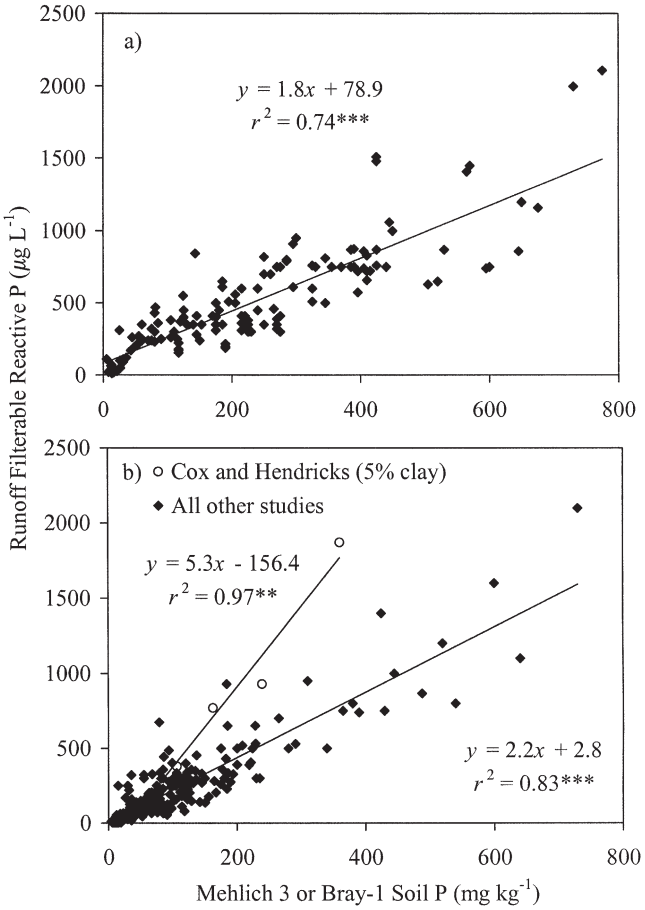

Fig. 1. Relationship between Mehlich 3– or Bray 1–extractable soil P and runoff filterable reactive phosphorus (FRP) for (a) the soil box studies of Fang et al. (2002), Kleinman and Sharpley (2003), Kleinman et al. (2002), Kleinman et al. (2004), McDowell and Sharpley (2001a), and Weld et al. (2001), and (b) the field-plot studies of Andraski and Bundy (2003), Andraski et al. (2003), Cox and Hendricks (2000), Daverede et al. (2003), Sharpley et al. (2001), and Turner et al. (2004) using tilled and no-till field plots.

Comparison of Studies Using Tilled and No-Till Field Plots

We used data from Andraski and Bundy (2003), Andraski et al. (2003), Cox and Hendricks (2000), Daverede et al. (2003), Sharpley et al. (2001), and Turner et al. (2004). The soils represented a wide range of physicochemical properties (Table 1). For the 10 soil types represented, extraction coefficients were not significantly different for nine soils, ranging from 1.2 to 3.0. (Fig. 1b). Only the extraction coefficient for the 5% clay soil of Cox and Hendricks (2000), which comprised only five observations, was significantly greater at 5.3. The most obvious explanation for this greater extraction coefficient was that the low soil clay content resulted in weakly adsorbed soil P that was more readily desorbed to rain-

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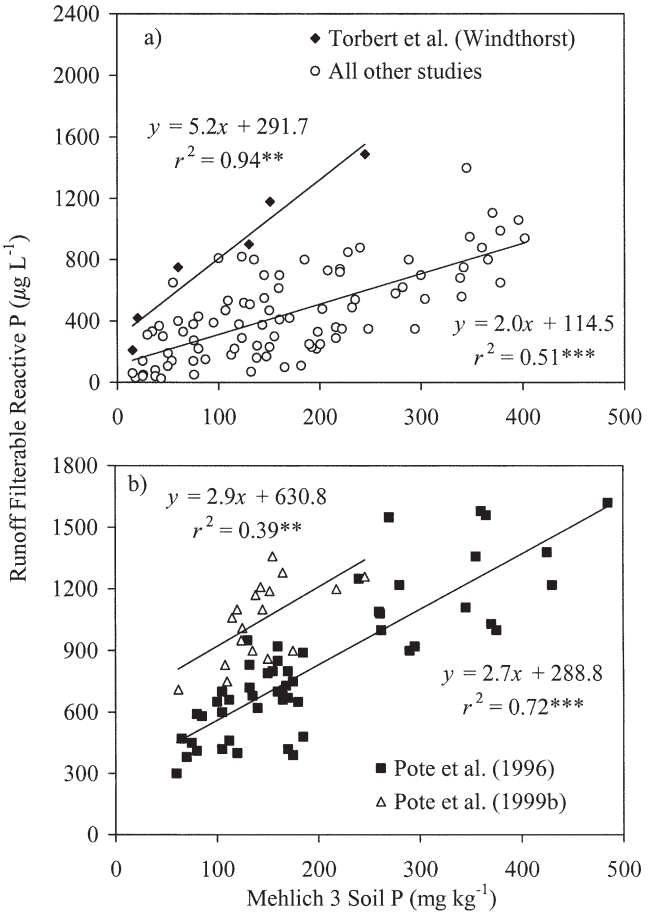

Fig. 2. Relationship between Mehlich 3–extractable soil P and runoff filterable reactive phosphorus (FRP) for the grassed field-plot studies of (a) Pote et al. (1999a, 1999b; May experiments), Schroeder et al. (2004), and Torbert et al. (2002), and of (b) Pote et al. (1996, 1999a; August experiments).

fall-runoff water (Sharpley, 1983). However, this explanation did not hold true for the range of soil clay contents (10–40%) in the remaining studies, which comprised more than 230 observations.

Comparison of Studies Using Grassed Field Plots

We used data from Pote et al. (1996, 1999a, 1999b), Schroeder et al. (2004), and Torbert et al. (2002) (Table 1). Extraction coefficients did not differ significantly for 10 of 11 soils, ranging from 1.4 to 3.6 (Fig. 2a). Only the noncalcareous Windthorst soil from Torbert et al. (2002) had a greater extraction coefficient (5.2). The Windthorst soil had no obvious property that might explain its greater extraction coefficient. However, extraction coefficients from Torbert et al. (2002) were determined from only six data points per soil, while extraction coefficients from other studies conducted on grassed field plots had at least 12 data points. Therefore, the significantly greater extraction coefficient for the Windthorst soil may partly be due to variability inherent in determining regression slopes with few data points.

Runoff dissolved P concentrations per unit of soil P tended to be greater for data of Pote et al. (1996, 1999a) when rainfall simulations were conducted on fescue plots in summer and early fall. The most obvious explanation is that fescue material in these months was either dormant or dead and was contributing more P to runoff than in spring or later fall months (Daniel et al., 1993; Sharpley, 1981; Sauer et al., 2000). Because extraction coefficients themselves were unaffected by the increase in runoff FRP, P release from plant material apparently does not affect P release from soil and simply increases FRP in runoff by consistent amounts at all concentrations of soil P. For clarity, we present the data from Pote et al. (1996, 1999a) in Fig. 2b.

Comparison of Soil Box and Field-Plot Studies

Figures 1 and 2 show that for a given management practice or experimental condition, such as only soil boxes, extraction coefficients did not vary significantly for the majority of soil types. Furthermore, the average of extraction coefficients was similar for experiments using soil boxes (1.8), tilled and no-till field plots (2.2), and grassed field plots (2.5). This suggests that it is reasonable to compare extraction coefficients for all three study types even though management practices and methods used to generate data differed. We therefore compared extraction coefficients from box studies of Fang et al. (2002), Kleinman and Sharpley (2003), Kleinman et al. (2002, 2004), McDowell and Sharpley (2001a), and Weld et al. (2001), tilled and no-till field-plot studies of Andraski and Bundy (2003), Andraski et al. (2003), Cox and Hendricks (2000; 30% clay soil only), Daverede et al. (2003), Sharpley et al. (2001), and Turner et al. (2004), and grassed field-plot studies of Pote et al. (1996, 1999a, 1999b), Schroeder et al. (2004), and Torbert et al. (2002; Windthorst soil omitted). We found that extraction coefficients for soils of Fang et al. (2002; 5.2) and for Nella (3.2) and Linker (3.7) soils of Pote et al. (1999b) were significantly greater, but that all other extraction coefficients were not significantly different, ranging from 1.2 to 3.0. Figure 3 presents data from all studies where extraction coefficients did not significantly differ, with data from Pote et al. (1996, 1999a) on summer and fall fescue plots separated for clarity. Interestingly, extraction coefficients for the significantly different soils of Fang et al. (2002) and Pote et al. (1999b) were not significantly different in previous comparisons, such as among soil boxes or grassed field plots alone. Apparently, the statistical procedure became sensitive to these greater extraction coefficients as the number of data points increased.

Of the studies we investigated, 5 of the 31 soil types had significantly greater extraction coefficients. These were the Windthorst (5.2) soil from Torbert et al. (2002), Nella (3.2) and Linker (3.7) soils of Pote et al. (1999b), soils of Fang et al. (2002; 5.2), and the 5% clay soil (5.3) of Cox and Hendricks (2000). These greater extraction coefficients were not consistently explained by reported soil physicochemical properties. For example, Cox and Hendricks (2000) suggested that the 5% clay content in their soil explained the greater extraction coefficient. However, clay content could not explain the greater extraction coefficient of the Windthorst soil of Torbert

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et al. (2002), as this soil had the same clay content as two other Torbert et al. (2002) soils with lesser extraction coefficients. Similarly, of the three soils investigated by Pote et al. (1999b), the Nella and Linker soils had greater extraction coefficients than the Noark soil, but the Noark soil had the least clay content. Significantly greater extraction coefficients were also not consistently explained by soil management practices, as the extraction coefficient of the soils of Fang et al. (2002) was greater than extraction coefficients for other soil box experiments, and extraction coefficients from studies of Pote et al. (1999b) and Torbert et al. (2002) varied even though all experiments were conducted on similar grassed plots. Pote et al. (1999b) suggested that their Nella and Linker soils had greater extraction coefficients because the volume of runoff relative to the volume of rainfall applied to plots was greater. Thus, more P that desorbed from soil was transported in runoff than in infiltrating water. Torbert et al. (2002) and Cox and Hendricks (2000) did not report runoff data from their field plots, so we could not confirm this hydrology phenomenon for their significantly different extraction coefficients.

Even though the extraction coefficients for the majority of investigated soils did not differ, the existence of significantly greater extraction coefficients may justify the use of variable coefficients in computer models for extreme soil properties, such as very high or very low clay content, or extreme hydrologic conditions, such as large or small amounts of runoff relative to rainfall. A more controlled investigation of these variables may provide more justification for variable extraction coefficients than our literature review could establish.

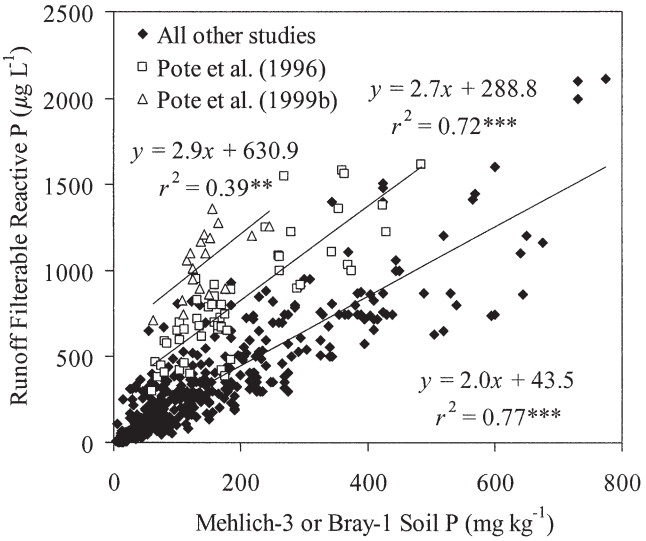

Fig. 3. Relationship between Mehlich 3– or Bray 1–extractable soil P and runoff filterable reactive phosphorus (FRP) for all studies using soil boxes, and tilled, no-till, and grassed field plots where extraction coefficients are not significantly different. Data are from Andraski and Bundy (2003), Andraski et al. (2003), Cox and Hendricks (2000), Daverede et al. (2003), Kleinman and Sharpley (2003), Kleinman et al. (2002, 2004), McDowell and Sharpley (2001a), Pote et al. (1996, 1999a, 1999b), Schroeder et al. (2004), Sharpley et al. (2001), Torbert et al. (2002), Turner et al. (2004), and Weld et al. (2001).

Literature Review of Studies Using Environmental Soil Tests

Water-Extractable Soil Phosphorus

We compared extraction coefficients for Aase et al. (2001), Andraski and Bundy (2003), Andraski et al. (2003), Daverede et al. (2003), Pote et al. (1996, 1999a, 1999b), Schroeder et al. (2004), Torbert et al. (2002), and Turner et al. (2004), which were conducted with soil boxes or on grassed, tilled, or no-till field plots and used the same procedure to determine water-extractable soil P. For the 10 studies and 20 soils, extraction coefficients did not differ significantly for 17 soils, ranging from 6.0 to 18.3 (Fig. 4a). Data in Fig. 4a for the summer rainfall simulations on fescue plots of Pote et al. (1999a) are separated for clarity. The remaining data revealed a strong relationship between water-extractable soil P and runoff FRP.

Of the soils investigated, extraction coefficients were significantly greater for only the Windthorst (28.7) soil

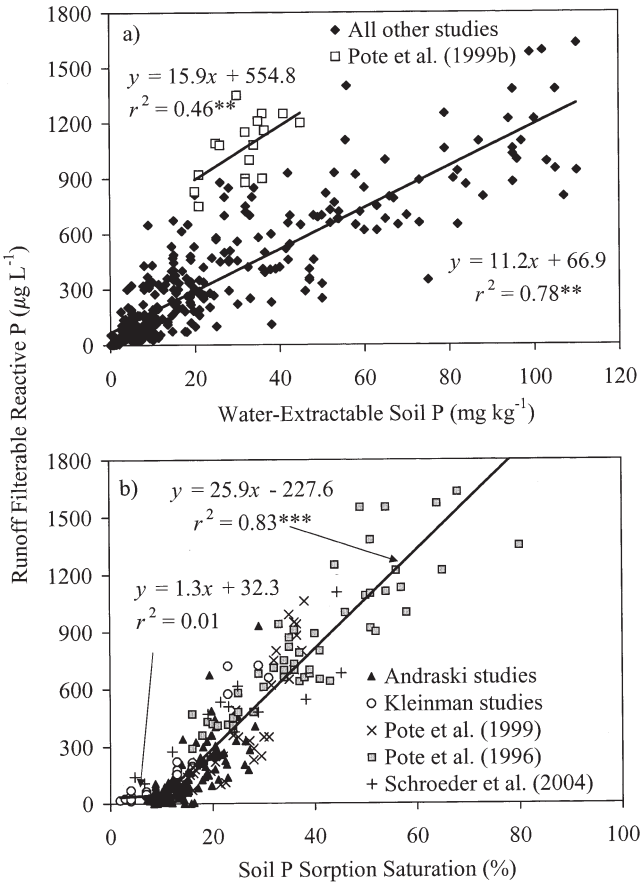

Fig. 4. Relationship between (a) water-extractable soil P and runoff filterable reactive phosphorus (FRP) from soil box and grassed and cropped field-plot studies of Aase et al. (2001), Andraski and Bundy (2003), Andraski et al. (2003), Daverede et al. (2003), Pote et al. (1996, 1999a, 1999b), Schroeder et al. (2004), and Torbert et al. (2002) where extraction coefficients did not differ significantly. Data from Pote et al. (1999a; August experiments) are presented separately for clarity. Relationship between (b) soil P sorption saturation and dissolved P in runoff from soil box and grassed and cropped field plot studies of Andraski and Bundy (2003), Andraski et al. (2003), Kleinman and Sharpley (2003), Kleinman et al. (2002, 2004), Pote et al. (1996, 1999b), and Schroeder et al. (2004).

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of Torbert et al. (2002) and were significantly less for only the Noark (5.7) soil of Pote et al. (1999b) and the Lancaster (5.7) soil of Andraski and Bundy (2003). As with the Mehlich-3 and Bray-1 P data, soil physicochemical properties, management conditions, or hydrology did not consistently explain variability in extraction coefficients determined from water-extractable soil P. Interestingly, when using Mehlich-3 and Bray-1 P data, extraction coefficients for the Noark and Lancaster soils were not significantly different from most other extraction coefficients. Conversely, Mehlich-3 soil P extraction coefficients for the Nella and Linker soils of Pote et al. (1999b) differed significantly from most other Mehlich-3 soil P extraction coefficients. Water-extractable soil P extraction coefficients for these soils did not differ from other soils. Therefore, variability among extraction coefficients may be as much a function of the method used to estimate soil P as soil properties, runoff hydrology, or management practices. This presents some potential problems when interpreting extraction coefficient variability for data sets from only one soil P test.

Soil Phosphorus Sorption Saturation

When relating soil P sorption saturation to runoff dissolved P, we used data from Andraski and Bundy (2003), Andraski et al. (2003), Kleinman and Sharpley (2003), Kleinman et al. (2002, 2004), Pote et al. (1996, 1999b), and Schroeder et al. (2004). These studies represented only noncalcareous soils. When plotted as discrete data sets from individual studies, extraction coefficients from these data varied significantly, ranging from 0.8 to 78.0. However, when all data were plotted together, there was a clear relationship between soil P sorption saturation and runoff FRP (Fig. 4b). This relationship exhibited a distinct change point at a soil P sorption saturation value of about 12, as determined visually. At soil P sorption saturation values less than the change point, runoff FRP was less than 100 $\mu g\ L^{-1}$ and was fairly consistent. At soil P sorption saturation values greater than the change point, runoff FRP increased rapidly.

Other studies have observed similar change-point relationships between soil P sorption saturation and dissolved P concentrations in soil leachate (Maguire and Sims, 2002; McDowell and Sharpley, 2001b) and P concentrations in water or weak-salt soil extracts (Hooda et al., 2000; Kleinman et al., 2000, Nair et al., 2004). Furthermore, the slope for the data in Fig. 4b where soil P sorption saturation values were greater than the change point was 25.9, a value similar to those reported by Kleinman et al. (2000) and McDowell and Sharpley (2001b), but much less than that reported by Maguire and Sims (2002). In the Netherlands, a critical degree of soil P sorption saturation has been set at 25%, to limit dissolved P concentrations in leachate to less than 100 $\mu g\ L^{-1}$ (Schoumans and Groenendijk, 2000). Because soil Fe and Al content is multiplied by a factor of 0.5 to calculate P sorption saturation in the Netherlands, these 25% (equal to 12.5% in Fig. 4b) and 100 $\mu g\ L^{-1}$ parameters agree with our results in Fig. 4b.

Extractions coefficients calculated using water-extractable soil P data were significantly less for the Noark soil of Pote et al. (1999b) and the Lancaster soil of Andraski and Bundy (2003) compared with those for most other soils investigated. For these two soils, the relationship between soil P sorption saturation and runoff FRP did not differ from that of other soils. Similarly, extraction coefficients calculated using Mehlich-3 soil P data were significantly greater for the Nella and Linker soils of Pote et al. (1999b) compared with extraction coefficients for most other soils. For these two soils, the relationship between soil P sorption saturation and runoff FRP did not differ from that of other soils. Therefore, for noncalcareous soils, a test for soil P sorption saturation may provide a more universal prediction of dissolved P in runoff than Mehlich-3, Bray-1, or water extractions.

Implications for Water Quality Modeling

Figure 3 shows that for 17 studies and 31 soil types, extraction coefficients determined using Mehlich-3 or Bray-1 soil P data did not differ significantly for 26 soils. Currently, many water quality models, such as EPIC (Williams et al., 1983) or SWAT (Arnold et al., 1998), use a single, constant value for an extraction coefficient for many soil types, management practices, and runoff conditions. Even though these models were typically developed before large amounts of data relating soil P to runoff FRP existed, Fig. 3 suggests that this single extraction coefficient method is justified for most modeling situations. Using Mehlich-3 or Bray-1 soil P data, runoff dissolved P concentrations ($\mu g\ L^{-1}$) can thus be predicted by multiplying soil P concentrations by 2.0.

There was no more relative variability among extraction coefficients calculated using water-extractable soil P data than using Mehlich-3 or Bray-1 soil P data. For water P extraction coefficients, 17 of 20 coefficients were not significantly different. This suggests that for a standardized method, a water extraction is as reliable as Mehlich-3 or Bray-1 agronomic tests for estimating dissolved P in runoff. Thus, runoff dissolved P concentrations ($\mu g\ L^{-1}$) can be predicted by multiplying water-extractable soil P concentrations, as estimated with the procedure in the investigated studies, by 11.2. In fact, for the studies of Andraski and Bundy (2003), Andraski et al. (2003), Daverede et al. (2003), Pote et al. (1999b; Noark soil omitted), Schroeder et al. (2004), Torbert et al. (2002), and Turner et al. (2004) where both Mehlich-3 and water-extractable soil P data were available, predicting runoff dissolved P from either Mehlich 3 using the equation in Fig. 3 or water-extractable soil P using the equation in Fig. 4a gave similar results (Fig. 5). Sharpley et al. (2004) found that such runoff P predictions with Mehlich-3 or water-extractable soil P data did not give similar results for high P soils with a long history of manure application. This may be due to different methods used for soil water P extractions, differences in runoff P prediction equations for Mehlich-3 soil P data, and differences in manure application history and subsequent soil chemistry.

Some research has shown a greater potential for varia-

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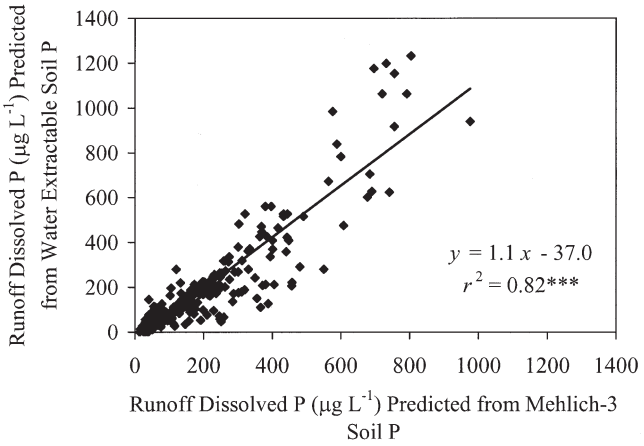

Fig. 5. Relationship between runoff dissolved P (μg L^{-1}) as predicted from water-extractable soil P and the equation in Fig. 4a or from Mehlich-3 soil P and the equation in Fig. 3. Soil P data are from Andraski and Bundy (2003), Andraski et al. (2003), Daverede et al. (2003), Pote et al. (1999b; Noark soil omitted), Schroeder et al. (2004), and Torbert et al. (2002).

tion in the concentration of soil P measured by a water extraction than by a Mehlich-3 or Bray-1 extraction. For example, Pote et al. (1999a) observed that water-extractable soil P varied depending on soil moisture content at the time of soil sampling and the method of drying soil samples. Mehlich-3 soil P did not vary for these different conditions. Therefore, even though Mehlich-3 and Bray-1 tests may not represent the interaction of soil and rainfall or runoff water as realistically as a water extraction, they may be more useful for estimating dissolved P in runoff because they are more consistent across a wide range of soil, management, or experimental conditions. Because Bray 1 may not accurately estimate available soil P in calcareous soils (Mallarino, 1997), Mehlich 3 is the more consistent of the two tests. This does not suggest that Mehlich 3 should become a universal agronomic soil P test, as various regions and countries have developed agronomic tests most suitable for their soils and crops.

Figures 3 and 4a show that for the majority of soils, management practices, runoff conditions, and experimental methods, a single extraction coefficient generated from either Mehlich-3, Bray-1, or water-extractable soil P can be used to estimate dissolved P concentrations in runoff for most modeling scenarios. However, Fig. 4b suggests that a test for soil P sorption saturation may ultimately provide the most universal method to predict dissolved P in runoff, at least for noncalcareous soils (Guo and Yost, 1999). This scenario was demonstrated by Sharpley (1995) when investigating the ability of various soil tests to predict dissolved P in runoff from soils recently amended with poultry litter. However, our results were not directly comparable because Sharpley (1995) calculated soil P sorption saturation as the Mehlich-3 soil P content divided by the soil P sorption maximum as estimated with P sorption isotherms. For modeling purposes, a test for soil P sorption saturation may require greater input data, as soil Fe and Al content or P sorption capacity must be known. However, because research investigates the potential for Fe- or Al-rich amendments to bind P and reduce its availability to transport in runoff (Haustein et al., 2000; Novak and Watts, 2004), a test for soil P saturation may also offer greater model flexibility as it could account for such changes in soil Fe or Al content.

CONCLUSIONS

Concern over P transfer from agricultural soils to surface waters continues to influence scientific research and environmental policy. One essential tool used in the effort to minimize such P transfer is computer modeling. Most models use constant values for extraction coefficients to estimated dissolved P in runoff from soil P concentrations, even though it is often assumed that such coefficients should vary as a function of soil properties, management conditions, or runoff hydrology. Our literature review of 17 independent studies that reported extraction coefficients using Mehlich-3 and Bray-1 soil P data for a wide variety of soil properties, management conditions, and runoff hydrology, revealed that extraction coefficients for 26 of the 31 soils did not differ significantly. For 10 studies and 20 soils, extraction coefficients developed from water-extractable soil P data did not differ significantly for 17 soils. Therefore, the agronomic Mehlich-3 and Bray-1 soil tests are equally, if not more, effective for evaluating the potential for soils to release dissolved P to runoff as the environmentally oriented water extraction test. The Mehlich-3 test may be more effective than the Bray-1 test for calcareous soils. For 6 studies representing 10 noncalcareous soils, the relationship between runoff FRP and soil P sorption saturation, as estimated with an ammonium oxalate test, did not differ for any of the data. Therefore, a test for soil P saturation may provide the most universal prediction of dissolved P in runoff, but only for noncalcareous soils.

Water quality models are widely used to evaluate P export and critical source areas within a watershed, and to assess which management practices can be implemented to decrease P export. Such models should accurately represent the physical systems they simulate, yet avoid complexity that renders them inefficient. The assumption that P extraction coefficients are specific to soil types, runoff conditions, or management practices implies greater complexity for modeling, but we have shown that a single value for an extraction coefficient relating soil P to dissolved P in runoff can be used across a wide range of soil, hydrology, or management scenarios. Thus, predicting dissolved P loss from soil to runoff can apparently remain simple without sacrificing model accuracy.

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