

DIVISION S-8—NUTRIENT MANAGEMENT & SOIL & PLANT ANALYSIS

Relationships Between Soil Test Phosphorus, Soluble Phosphorus, and Phosphorus Saturation in Delaware Soils

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ABSTRACT

Methods to identify agricultural soils that contribute to nonpoint-source pollution of surface waters by P are of increasing importance, particularly in areas with high animal densities (animal units per hectare of cropland). Our objective was to determine the relationship between agronomic soil test P (STP = Mehlich 1) and other soil P tests proposed to measure the potential for P loss by erosion, runoff, and leaching. We compared STP with soluble P, P in the “fast desorbing pool” (strip P), and soil P saturation for 127 soils (122 from Delaware and five from the Netherlands). Soil test P was significantly correlated with total P ($r = 0.57^{***}$, significant at the 0.001 level), soluble P ($r = 0.71^{***}$), strip P ($r = 0.84^{***}$), and oxalate-extractable P (P_{ox} ; $r = 0.84^{***}$). Strip P was a better predictor of soluble P than STP ($r^2 = 0.76^{***}$). The ratio of strip P/ P_{ox} (the percentage of reversibly sorbed P in the fast desorbing pool) increased as P sorption capacity, estimated from oxalate-extractable Al and Fe ($Al_{ox} + Fe_{ox}$), decreased. We also determined the degree of P saturation (DPS) using three methods: Langmuir P sorption isotherms; oxalate extractions of P, Al, and Fe; and STP plus a single-point P sorption index (PSI). Soluble P, STP, and desorbable P increased for DPS values $>30\%$, similar to upper DPS limits in the Netherlands and Belgium. Soils rated agronomically excessive in STP ($>50 \text{ mg kg}^{-1}$) had higher ratios of soluble P, strip P, and P_{ox} to total P than those in agronomically optimum or lower categories.

THE IMPACT OF AGRICULTURAL P on surface and ground water quality is an issue of growing international concern, particularly in areas dominated by geographically intensive animal agriculture (i.e., agriculture where a large number of animal units are produced per hectare of cropland available for land application of manures and other animal by-products) (Breeuwsma et al., 1995; Edwards and Withers, 1998; Sharpley et al., 1998; Simard et al., 1995; Sims, 1997). Farm- and regional-scale P surpluses are common in animal agriculture because inputs of P in feed and fertilizers are almost always greater than the outputs of P in animal products and crops (Brouwer, 1998; Sims et al., 1999; Tunney, 1990). Because of the lack of economically viable alternatives, surplus P (which is concentrated in animal wastes) is almost always applied to cropland, usually at rates that provide more P than is needed for optimum crop production. Soil P concentrations then build to values that are considered *very high* or *excessive* from

an agronomic perspective and soils become increasingly saturated with P (De Smet et al., 1996; Lookman et al., 1996; Schoumans and Groendijk, 1999). Laboratory research conducted for the past 10 to 15 yr has shown that soils with high agronomic soil test P (STP) values are more likely to have high concentrations of soluble, desorbable, and bioavailable P (Sibbesen and Sharpley, 1997; Sims, 1998). Field studies have shown that P losses by erosion, surface runoff, and leaching-lateral subsurface flow are greater when STP values are above the agronomically optimum range (Beauchemin et al., 1998; Heckrath et al., 1995; Pote et al., 1996; Sims et al., 1998).

Delaware is the site of one of the most concentrated poultry industries in the USA, producing about 260 million broiler chickens each year in a state with $\approx 225,000$ ha of cropland (DDA, 1998). Most ($>90\%$) poultry are produced in Sussex County, Delaware, which has $\approx 100,000$ ha of cropland. It has been estimated that based on fertilizer consumption and poultry litter production alone, annual P surpluses of 16 and 49 kg P ha $^{-1}$ exist statewide and in Sussex County, respectively (Cabrera and Sims, 1999). Furthermore, applying poultry litter based on crop N requirements adds ≈ 135 kg P ha $^{-1}$, relative to crop P removal of 25 kg P ha $^{-1}$ (Mozaffari and Sims, 1994). Because of these P surpluses and the historical use of N-based manure management practices, the amount of P in manure applications has often exceeded the amount of P removed by crop harvest. This has resulted in the widespread buildup of soil P to values well above those needed for optimum crop production. For example, recent soil test summaries from Delaware ($\approx 14,000$ samples from 1992–1997) showed that 92% of the agricultural soils tested from Sussex County are now optimum or excessive in STP (Sims, 1998). The median STP value (Mehlich 1) was 70 mg P kg $^{-1}$ and 30% of the soils tested were >100 mg P kg $^{-1}$. In comparison, the Mid-Atlantic Soil Test and Plant Analysis Work Group (a regional consortium of public and private soil test laboratories) stated in 1997 that for corn (*Zea mays* L.), a Mehlich 1 value of 20 mg P kg $^{-1}$ was the “soil test P level at 100% yield,”

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Abbreviations: Al_{ox} , Fe_{ox} , P_{ox} , aluminum, iron, and phosphorus extracted by acid ammonium oxalate; DPS, degree of soil P saturation; ICP-AES, inductively coupled plasma atomic emission spectroscopy; OM, organic matter; P_w , water soluble P; PSC_r , remaining P sorption capacity; PSC_t , total P sorption capacity; PSI, single-point P sorption index; STP, soil test P; UDSTP, University of Delaware Soil Testing Program.

and 35 mg P kg⁻¹ was the “soil test P level where no fertilizer is recommended” (Sims, 1998).

Soil P testing is now used in some countries and U.S. states and is under consideration in others as a means to identify areas where P applications in fertilizers and manures should be prohibited to protect water quality (Sibbesen and Sharpley, 1997; Sims et al., 1999). The rationale for these actions is three-fold: First, building soil test P above agronomic optimum values is perceived as an inefficient use of a limited natural resource (phosphate). Second, soils with higher STP concentrations are considered more likely to lose P to surface waters by erosion and surface or subsurface runoff. And, third, geographic summaries of agronomic STP results are readily available in most states. These summaries provide a large, historical database on soil P status, which can be related to soil management practices, cropping systems, and soil properties. If STP is related to the potential for P loss to ground or surface waters, this database could be used in state or regional planning efforts to reduce nonpoint-source pollution.

Consequently, our objectives were (i) to determine if quantitative relationships exist between agronomic STP values and P measurements that are proposed as indicative of the potential for P loss to waters, such as soluble P, easily desorbable P, and the degree of P saturation, and (ii) to assess which soil P testing methods would be most easily adopted by routine soil testing laboratories that may soon be asked to provide environmental, as well as agronomic, P recommendations.

MATERIALS AND METHODS

We obtained 122 agricultural topsoil (0–20 cm) samples from the archives of the University of Delaware Soil Testing Program (UDSTP) for this study. The soils represented the range of STP, pH, textural class, and organic matter (OM) in Delaware's three counties (New Castle, Kent, and Sussex) and are typical of many soils in the Mid-Atlantic states. The number of soils from each county was based on the percentage of samples submitted to the UDSTP each year (New Castle: 12%; Kent: 23%; Sussex: 65%). Five Dutch soils were provided for comparison by the Winand Staring Centre for Integrated Land and Water Research (SC-DLO) in the Netherlands. Soil pH, OM, and acid ammonium oxalate-extractable Al and Fe [Al_{ox} and Fe_{ox}; 1:40 ratio of soil to (NH₄)₂C₂O₄; 2-h reaction time in darkness] were determined by standard methods of the UDSTP (Table 1; Sims and Heckendorn, 1991).

Soil Phosphorus Characterization

The following P measurements were conducted on all 127 soils: (i) STP was measured by Mehlich 1 extraction [1:4 ratio of soil to 0.05 M HCl + 0.0125 M H₂SO₄; 5-min reaction time (Sims and Heckendorn, 1991)]; (ii) dilute salt-soluble P [1:10 ratio of soil to 0.01 M CaCl₂; 1-h reaction time (Kuo, 1996)]; (iii) Fe oxide-strip P [1:40 ratio of soil to 0.01 M CaCl₂ + Fe-oxide-coated filter paper strip; 16-h reaction time, followed by desorption of P with 1 M H₂SO₄ (Chardon et al., 1996)]; (iv) acid ammonium oxalate-extractable P (P_{ox}) (McKeague and Day, 1966; Schwertmann, 1964); and (v) total P by perchloric acid digestion (Kuo, 1996). We also measured water soluble P [P_w; equilibrate 1.2 g soil with 2 mL deionized water for 20 h, add 25 mL deionized water, shake 16 h and centrifuge (Sissingh, 1971)] on a subset of 41 soils selected for P sorption

studies (see below). All solutions, except for STP and P_{ox}, were analyzed for P colorimetrically by the molybdate-blue method of Murphy and Riley (1962). Oxalate-extractable P, Al, and Fe, and STP were measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES).

Phosphorus Sorption Parameters

A representative subset (41 soils) of the 127 Delaware and Dutch soils was selected for characterization of P sorption capacity (Table 1). Phosphorus sorption isotherms were conducted by a modification of the standard batch technique of Nair et al. (1984). Thirty milliliters of six P solutions ranging in initial concentrations from 0 to 25 mg P L⁻¹ (as KH₂PO₄) were equilibrated with 2.0 g of each soil in 50-mL test tubes in an end-over-end shaker. The soil suspension was then centrifuged, filtered through 0.45-μm Gelman millipore filters, and analyzed for P by ICP-AES. The difference between P added in the initial solutions and P remaining in the filtered solutions was considered to have been sorbed.

The P sorption index (PSI), a rapid means to estimate soil P sorption capacity, was also determined for these 41 soils (Bache and Williams, 1971; Mozaffari and Sims, 1994). The PSI was calculated as the amount of P sorbed (mg kg⁻¹) after equilibration of 0.4 g soil with 40 mL of a 15 mg P L⁻¹ solution (as KH₂PO₄, equivalent to 1.5 g P kg⁻¹ soil) in an end-over-end shaker for 24 h, followed by centrifugation, filtration, and analysis for P by ICP-AES.

Soil Phosphorus Saturation

We determined the degree of soil P saturation (DPS) by three methods:

(i) DPS_{Langmuir}: In this approach we calculated DPS for the 41 subset soils only, as

$$\text{DPS}_{\text{Langmuir}} (\%) = P_{\text{ox}} / (\text{PSC}_t) \times 100$$

$$\text{PSC}_t = (P_{\text{ox}} + \text{PSC}_r)$$

where PSC_t is the total P sorption capacity of a soil, P_{ox} is the amount of P already sorbed, and PSC_r is the remaining P sorption capacity. We estimated PSC_r from P sorption maxima calculated from the linearized version of the Langmuir equation using experimental data from P sorption isotherms conducted with the 41 soils (Olsen and Watanabe, 1957).

(ii) DPS_{STP}: We also estimated DPS for the 41 soils using the ratio of STP to (PSI + STP):

$$\text{DPS}_{\text{STP}} (\%) = \{ \text{STP (mg kg}^{-1}) / [\text{PSI} + \text{STP (mg kg}^{-1})] \} \times 100$$

(iii) DPS_{ox}: We also used the approach of van der Zee and van Riemsdijk (1988) and calculated DPS in all 127 soils based on P_{ox}, Fe_{ox}, and Al_{ox}.

$$\text{DPS}_{\text{ox}} (\%) = [P_{\text{ox}} (\text{mmol kg}^{-1}) / \text{PSC}_t (\text{mmol kg}^{-1})] \times 100$$

$$\text{PSC}_t = \alpha [\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}} (\text{mmol kg}^{-1})]$$

where α is an empirical parameter calculated as the ratio of PSC_r (determined experimentally for a defined group of soils, in this case our 41 subset soils) to [Al_{ox} + Fe_{ox}].

RESULTS AND DISCUSSION

Soil Characteristics

The Delaware soils used in this study were representative of many soils in the coastal plain and Piedmont

Table 1. Selected soil chemical and physical properties for all 127 Delaware and Dutch soils and for the subset of 41 soils used for more detailed P sorption studies.

Property	Delaware soils	New Castle soils	Kent soils	Sussex soils	Dutch soils
	Mean \pm SD				
	All soils				
pH	5.9 \pm 0.6	6.4 \pm 0.4	6.0 \pm 0.6	5.9 \pm 0.6	5.7 \pm 0.7
OM, g kg ⁻¹	18 \pm 16	19 \pm 6	16 \pm 9	19 \pm 18	56 \pm 33
Al _{ox} , mmol kg ⁻¹	30 \pm 16	24 \pm 10	27 \pm 9.9	31 \pm 18	36 \pm 12
Fe _{ox} , mmol kg ⁻¹	11 \pm 16	15 \pm 4.2	15 \pm 21	9.3 \pm 14	25 \pm 18
P _{ox} , mmol kg ⁻¹	8.7 \pm 6.8	3.8 \pm 2.2	6.7 \pm 5.4	10 \pm 7.2	19 \pm 9.3
STP, mg kg ⁻¹	86 \pm 96	28 \pm 24	63 \pm 87	104 \pm 102	123 \pm 69
CaCl ₂ -P, mg kg ⁻¹	2.4 \pm 3.5	0.4 \pm 0.3	1.5 \pm 26	3.0 \pm 3.8	5.7 \pm 4.3
Strip P, mg kg ⁻¹	33 \pm 26	13 \pm 13	24 \pm 25	40 \pm 25	70 \pm 27
Total P, mg kg ⁻¹	507 \pm 242	598 \pm 172	510 \pm 199	492 \pm 263	634 \pm 139
	Subset soils†				
pH	5.7 \pm 0.6	6.2 \pm 0.8	5.8 \pm 0.6	5.7 \pm 0.6	5.7 \pm 0.7
OM, g kg ⁻¹	25 \pm 26	18 \pm 8	21 \pm 13	27 \pm 3	56 \pm 33
Al _{ox} , mmol kg ⁻¹	31 \pm 19	14 \pm 2.4	27 \pm 12	33 \pm 21	36 \pm 12
Fe _{ox} , mmol kg ⁻¹	15 \pm 28	14 \pm 10	23 \pm 37	12 \pm 25	25 \pm 18
P _{ox} , mmol kg ⁻¹	10 \pm 8.8	3.8 \pm 2.4	5.2 \pm 3.7	12 \pm 9.5	19 \pm 9.3
STP, mg kg ⁻¹	85 \pm 103	40 \pm 21	22 \pm 11	112 \pm 114	123 \pm 69
CaCl ₂ -P, mg kg ⁻¹	2.8 \pm 4.2	0.4 \pm 0.03	0.3 \pm 0.1	3.9 \pm 4.6	5.7 \pm 4.3
Strip P, mg kg ⁻¹	37 \pm 30	17 \pm 3.7	12 \pm 7.7	48 \pm 29	70 \pm 27
Total P, mg kg ⁻¹	554 \pm 271	560 \pm 209	508 \pm 208	570 \pm 300	634 \pm 139
P _s , mg kg ⁻¹	10 \pm 6.3	6.4 \pm 0.4	5.1 \pm 1.9	12 \pm 6.4	37 \pm 10

† Note: The subset of 41 soils was selected from the original 127 soils and used for additional, more detailed analyses.

regions of the Mid-Atlantic states. In general, the soils were moderately acidic and low in OM, although this varied slightly among counties (Table 1). Soils from New Castle county, located in the Piedmont plateau, are generally finer-textured (silt loams) than the coastal plain soils from Kent and Sussex counties (sandy loams and loamy sands). Dominant soil orders in New Castle and Kent counties are Ultisols (80–90%), Alfisols (9%), and Inceptisols (3%). Soils in Sussex county, for the most part, are very sandy with low OM contents; however, some soils have higher OM contents because of poor drainage. Major soil orders are Ultisols (57%), Entisols (33%), and Inceptisols (3%). The Dutch soils used in this study were also sandy and moderately acidic, but had higher contents of oxalate Al and Fe and OM than the Delaware soils (Table 1). The properties of the five Dutch soils compare reasonably well with those of Dutch topsoils used in studies of P sorption and saturation by van der Zee and van Riemsdijk (1988) (mean Al_{ox} = 35 mmol kg⁻¹; mean Fe_{ox} = 43 mmol kg⁻¹; $n = 84$) and Belgian topsoils investigated by Lookman et al. (1995b) (mean Al_{ox} = 48 mmol kg⁻¹; mean Fe_{ox} = 27 mmol kg⁻¹; $n = 301$).

Relationships Between Soil Test Phosphorus and Other Forms of Soil Phosphorus

The 122 Delaware soils were selected to be typical of the agricultural soils in the state and to provide a range and distribution in STP (Mehlich 1) values similar to that in each Delaware county today. The current STP rating scale used in Delaware is as follows: *low* (<13 mg P kg⁻¹), *medium* (13–24 mg P kg⁻¹), *optimum* (25–50 mg P kg⁻¹), and *excessive* (>50 mg P kg⁻¹) (Sims and Gartley, 1996). The mean STP value for all Delaware soils in our study was 86 mg P kg⁻¹ and mean STP values were greatest in Sussex county (104 mg P kg⁻¹), followed by Kent county (63 mg P kg⁻¹), and then New Castle

county (28 mg P kg⁻¹) (Table 1). Sims (1998) reported mean STP values, based on analysis of 12 000 agricultural soils of 79, 89, 67, and 40 mg P kg⁻¹ for the state of Delaware, Sussex, Kent, and New Castle counties, respectively. Soil test P values reflect the differing land uses in these counties. Sussex county is dominated by an intensive poultry industry and grain farming (\approx 230 million broiler chickens per year and 100 000 ha of cropland), Kent county by mixed agriculture (grain, vegetable, poultry), and New Castle county by grain crops with little intensive animal production. Soil test P values in all five Dutch soils (range = 70–220 mg P kg⁻¹; mean = 123 mg P kg⁻¹) would be rated as excessive and likely reflect a history of long-term manuring and fertilization.

One of the goals of this research was to quantify the relationships between STP and other tests for soil P. We found, based on all 127 soils (Delaware and Dutch), that STP was significantly correlated with total P ($r = 0.57^{***}$) (Fig. 1), oxalate-extractable P (P_{ox} , $r = 0.84^{***}$), Fe oxide-strip P ($r = 0.84^{***}$), and dilute salt (0.01 M CaCl₂)-extractable P ($r = 0.71^{***}$). Statistically significant linear or curvilinear regression equations were developed to predict P_{ox} , strip P, and 0.01 M CaCl₂-extractable P from STP ($r^2 = 0.70^{***}$, 0.81^{***} , and 0.50^{***} for P_{ox} , strip P, and 0.01 M CaCl₂-extractable P, respectively); however, the r^2 value for the STP–total P relationship was too low ($r^2 = 0.32$) for predictive purposes (Fig. 1). These results are consistent with past research. Beauchemin et al. (1996) reported that average values for water soluble P and P_{ox} increased with STP and were higher in soils from Canadian watersheds with surplus P from animal manures than in forested soils. Sharpley (1996) showed consistent increases in Fe oxide-strip P as STP (Mehlich 3) increased because of long-term applications of beef, poultry, and swine manures. Barberis et al. (1996) reported significant, positive correlations between several soil P tests and both

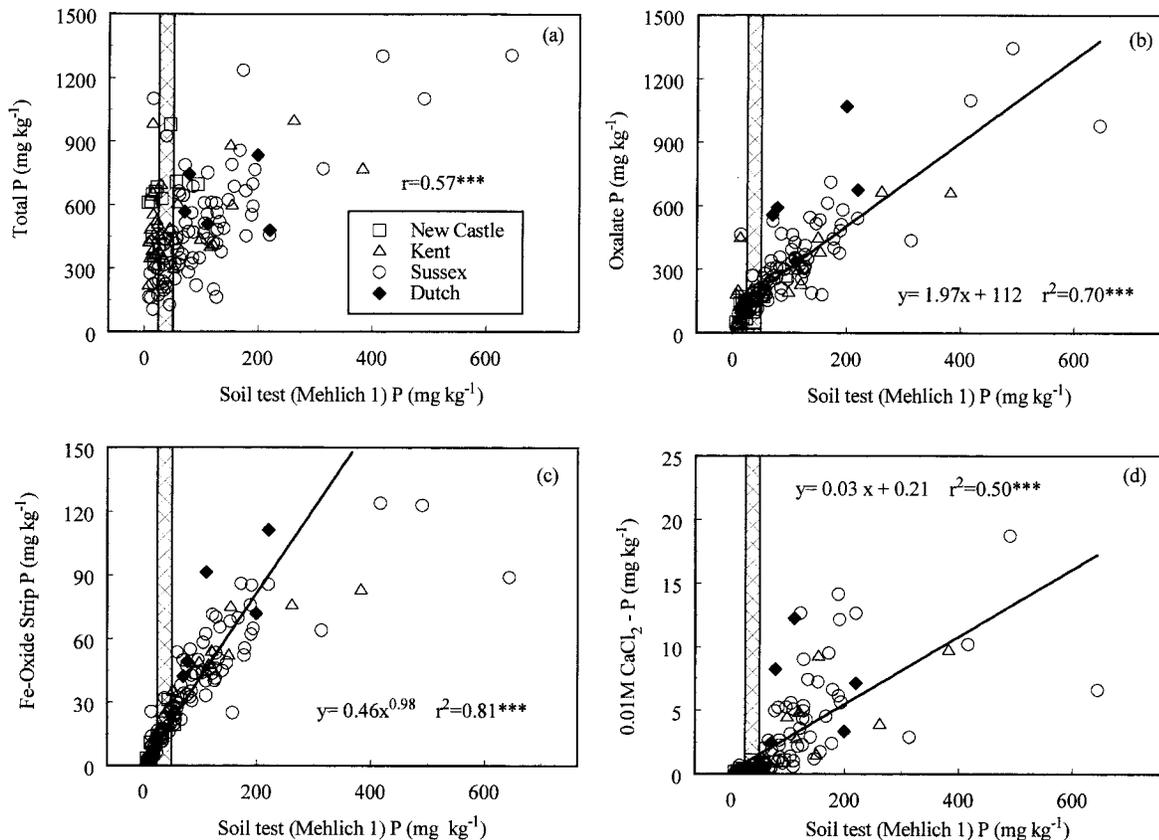


Fig. 1. Relationships between soil test P (Mehlich 1) and (a) total P, (b) oxalate P, (c) Fe oxide-strip P, and (d) dilute salt (0.01 M CaCl₂)-soluble P for all 127 soils. Hatched rectangles indicate the agronomically optimum range for soil test P (25–50 mg kg⁻¹) used by the University of Delaware.

Fe oxide-strip P ($r = 0.62^*$ to 0.89^{***}) and water soluble P ($r = 0.53^*$ to 0.88^{***}) for 12 over-fertilized European soils.

We also found that for all 127 soils, a significant linear relationship existed between total P and P_{ox} [total P = $(0.73)(P_{ox}) + 304$; $r^2 = 0.46^{***}$]. Our results differ from those of van der Zee and van Riemsdijk (1988), who reported a higher correlation coefficient ($r = 0.93^{***}$) and a near 1:1 relationship between total P and P_{ox} ($r = 0.93^{***}$) for 84 topsoils of the Netherlands. There were different relationships between P_{ox} and total P in soils from the three Delaware counties and the Dutch soils. Oxalate-extracted P made up $\approx 65\%$ of the total P from the coarse-textured soils of Sussex county, only 20% of total P in the fine-textured Piedmont soils of New Castle county, and 93% of the total P in the five Dutch soils (Table 1). For Sussex county soils, P_{ox} was better correlated with total P ($r = 0.80^{***}$) than when all 127 soils were considered together ($r = 0.68^{***}$).

In general, our data suggest that STP could be used to predict the concentrations of P_{ox} and desorbable P (strip P) with reasonable accuracy but would not be as reliable an indicator of total or soluble P (Fig. 1). Multiple-regression equations between STP and other forms of P that included parameters such as pH, OM, and oxalate Al and Fe gave only slight improvements in predictive accuracy relative to regressions with STP alone (data not shown). The most significant improve-

ment obtained was with total P, where the R^2 value for the relationship between total P and [STP and Fe_{ox}] was 0.56^{***} , compared with 0.36^{**} based only on STP.

Improved prediction of soluble P could be achieved by use of Fe oxide-strip P ($r^2 = 0.76^{***}$, Fig. 2a). Other research has shown that strip P may provide a more accurate way to estimate P desorption into runoff waters than STP (Pote et al., 1996; Sharpley et al., 1996), as well as the biological availability of P in sediments in agricultural runoff (Sharpley et al., 1994). We also observed that the ratio of Fe oxide-strip P to P_{ox} decreased in a curvilinear manner as the concentration of [$Al_{ox} + Fe_{ox}$] increased (Fig. 2b). This suggests that P-enriched soils with low concentrations of [$Al_{ox} + Fe_{ox}$] will have a higher percentage of easily desorbed P. Lookman et al. (1995a) found an almost identical trend in studies of the long-term kinetics of P desorption with 44 Belgian and German soils. They reported that most P_{ox} was reversibly sorbed, that Fe oxide-P represented a "fast desorbing pool" of soil P with a maximum value of 22% of P_{ox} , and that the ratio of Fe-oxide P to P_{ox} increased in a near linear manner as soils became increasingly saturated with P.

Characterizing Soil Phosphorus Saturation

Estimating the degree of P saturation (DPS) has been proposed as a means to predict the potential for P losses

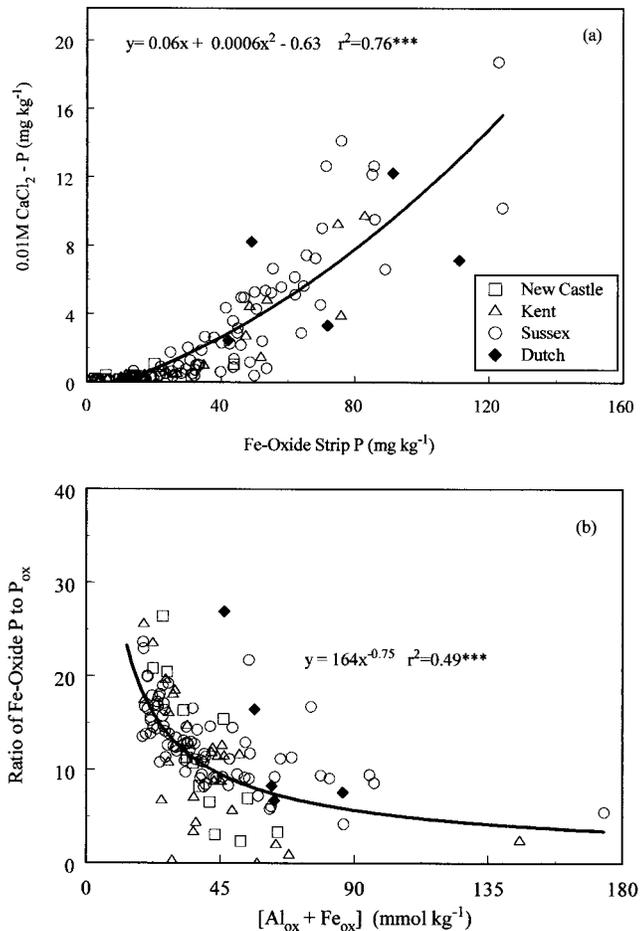


Fig. 2. Relationships between (a) dilute salt (0.01 M CaCl₂)-soluble P and Fe oxide-strip P and (b) the ratio of Fe oxide-strip P/P_{ox} and [Al_{ox} + Fe_{ox}] (based on all 127 soils).

in runoff and leaching under field conditions (Breeuwisma et al., 1995; De Smet et al., 1996; Lookman et al., 1996; Pote et al., 1996; Sharpley et al., 1996; Sims et al., 1998; van der Zee and van Riemsdijk, 1988). Soils with higher DPS values presumably have a greater risk of P loss to water because they will maintain higher P concentrations in the soil solution and because any eroded soil particles will be highly enriched with potentially desorbable P.

We determined DPS_{Langmuir} for the subset of 41 Delaware and Dutch soils (Table 1) and confirmed that concentrations of soluble P and the release of P into solution through desorption and dissolution reactions increased as soils become more saturated with P. Significant linear relationships existed between DPS_{Langmuir} and 0.01 M CaCl₂-P ($r^2 = 0.53^{**}$), P_w ($r^2 = 0.43^*$), STP ($r^2 = 0.48^{**}$), and strip P ($r^2 = 0.60^{***}$). However, further regression analysis indicated that curvilinear (exponential) equations better fit the data for these 41 soils in all cases ($r^2 = 0.65^{***}$ to 0.82^{***}) (Fig. 3a and b). Soil DPS values of 25 to 40% are commonly associated with greater risks of P loss in leaching or runoff and thus nonpoint-source pollution. Breeuwisma et al. (1995) stated that DPS values of >25%, in the soil profile to the depth of the mean high water table, would contribute to shallow

ground water pollution in the Netherlands. De Smet et al. (1996) reported mean DPS values of 57% for depths of 0 to 30 cm, 22% for depths of 30 to 60 cm, and 11% for depths of 60 to 90 cm in the profiles of 296 Belgian soils; a DPS value of 30% for depths of 0 to 90 cm in the soil profile was proposed as an upper limit to protect shallow ground waters. Pote et al. (1999) showed that dissolved reactive P in runoff from three Ultisols in Arkansas increased at DPS values $> \approx 20$ to 30%.

A rapid means for soil testing laboratories to characterize DPS (either for individual farms or as part of large-scale assessments of the potential for P loss to water) is needed because P sorption isotherms are too time-consuming and expensive for routine use. Research in the Netherlands and Belgium has shown that DPS_{ox} can be accurately estimated by acid ammonium oxalate extraction of soils for P, Al, and Fe (De Smet et al., 1996; Lookman et al., 1996; van der Zee and van Riemsdijk, 1988). Estimation of DPS_{ox} from P_{ox}, Al_{ox}, and Fe_{ox} requires information on α , an experimentally determined parameter that relates PSC_t (the sum of P_{ox} + PSC_t) to [Al_{ox} + Fe_{ox}]. Reported values of α for acid, sandy soils have usually ranged between 0.3 and 0.7 and an α value of 0.5 is commonly used, often without experimental justification (De Smet et al., 1996; Lookman et al., 1995b; Lookman et al., 1996; van der Zee et al., 1987). Past research has also shown that not only soil properties but the reaction time between added P and the soil will affect estimation of PSC_t and thus values of PSC_t and α . For example, van der Zee and van Riemsdijk (1988) reported an α value of 0.48 (SD = 0.09) for 84 Dutch topsoils based on 40-h sorption experiments but an α value of 0.61 (SD = 0.13) for the same soils based on a 249-d reaction time. Extending the length of the sorption experiment allows for slow P sorption to occur and thus increases the ratio of PSC_t to [Al_{ox} + Fe_{ox}]. Consequently, van der Zee and van Riemsdijk (1988) suggested multiplying short-term estimates of α by 1.8 to adjust for slow P sorption kinetics.

As with past research, we found for the 41 subset soils that PSC_t was significantly correlated with [Al_{ox} + Fe_{ox}] ($r = 0.61^{**}$; Fig. 4), providing further evidence that the P sorption capacity of acid, low OM soils is controlled by amorphous Al and Fe. The average α value for these 41 soils was 0.38 (SD = 0.14) [$\alpha = \text{PSC}_t / (\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}})$]. This is within the range of short-term estimates of α reported for Belgian, Dutch, and German soils (Lookman et al., 1995a; van der Zee et al., 1987). If multiplied by 1.8 to adjust for slow P sorption kinetics, an α value of 0.68 is obtained for our soils, very similar to the 0.61 value determined by van der Zee and van Riemsdijk (1988) for acid, sandy, low organic-matter topsoils in the Netherlands. We next calculated DPS_{ox} for all 127 soils, based on P_{ox}, Al_{ox}, and Fe_{ox} and using $\alpha = 0.68$. As with DPS_{Langmuir}, soluble and desorbable-extractable P increased linearly with DPS_{ox} (Fig. 3c and d).

Finally, we estimated DPS_{STP} from STP and a single-point P sorption index (PSI). The PSI has been shown to be a rapid, reliable means to estimate PSC_t in soils and sediments (Mozaffari and Sims, 1994; Reddy et al.,

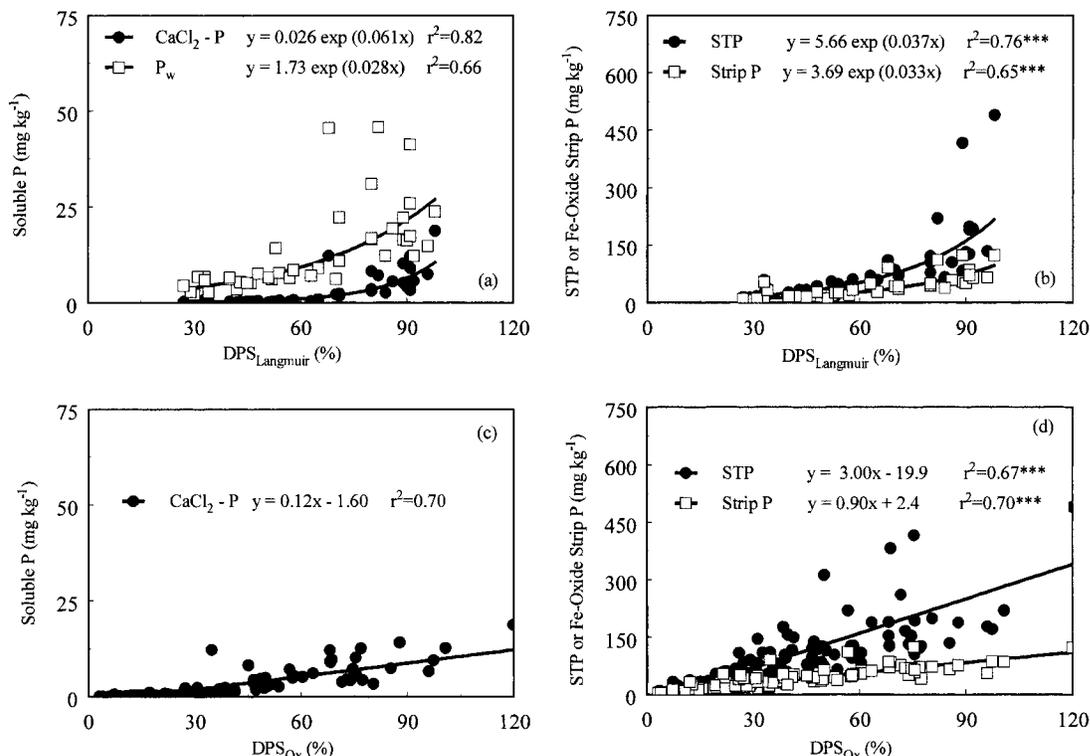


Fig. 3. Relationships for the 41 subset soils, between the degree of P saturation (calculated as the ratio of P_{ox} to PSC_t , where $\text{PSC}_t = \text{PSC}_r + \text{P}_{\text{ox}}$) and (a) dilute salt (0.01 M CaCl_2)-soluble P and P_w , and (b) soil test (Mehlich 1) and Fe oxide-strip P. Relationships, for all 127 soils, between the degree of P saturation [calculated as $\text{P}_{\text{ox}} \div [\alpha (\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}})]$, using $\alpha = 0.68$], and (c) dilute salt (0.01 M CaCl_2)-soluble P, and (d) soil test (Mehlich 1) and Fe oxide-strip P.

1998; Simard et al., 1995) and was recently shown by Pote et al. (1999) to be well correlated with dissolved P losses in runoff. The value of a soil test-based approach to estimating soil P saturation is that many farmers and advisory agencies already have extensive summaries of STP. Combining this existing database with a rapid, simple test for P sorption capacity could allow for more widespread characterization of soil P saturation on a farm or in a watershed. It is also possible that PSI could be estimated from soil series information, as has been done with DPS_{ox} in the Netherlands. For example, Mozaffari and Sims (1994) reported that PSI was significantly correlated with clay content ($r = 0.90^{***}$), which suggests that PSI groupings could be developed for a watershed based on textural class. We also found that PSC_r and PSI were highly correlated for the 41 subset soils ($r^2 = 0.94$, Fig. 5a) and that soluble P (0.01 M CaCl_2 -P and P_w) and P in the fast desorbing pool (Fe oxide-strip P) increased linearly with DPS_{STP} (Fig. 5b).

Relationship of Soil Test Categories to Soil Phosphorus and Soil Phosphorus Saturation

One of the major questions now being addressed to those involved in soil P testing is the appropriate value for an upper, environmentally based, critical limit for soil test P (Daniels et al., 1998; Sibbesen and Sharpley, 1997; Sims, 1998; Sims et al., 1999). Soils exceeding this critical limit would require greater management efforts (e.g., reduced tillage, buffer strips, grassed waterways,

reduction or elimination of further P applications) to prevent nonpoint-source pollution of surface waters by P. Gartley and Sims (1994) reported that upper critical limits for STP varied between states but were typically between three to six times the value accepted as adequate for optimum crop yields. At that time, most upper limits were recommended values and served only as guidelines, not as regulatory standards. Recently, some states and countries have begun to define STP values above which some form of P-based management must be practiced. In Ireland, for example, licensing programs for pigs and poultry now prohibit the application of animal wastes if STP (Morgan soil test) exceeds 15 mg P kg^{-1} (Irish EPA, 1997). In the USA, the state of Maryland will require use of the P Site Index system in all fields with Mehlich 1 STP values greater than three times the agronomic critical level (critical level = 25 mg P kg^{-1} ; upper limit = 75 mg P kg^{-1}) (F.J. Coale, University of Maryland, personal communication, 1999). The P Site Index characterizes the risk of P loss to surface waters based on STP, soil erosion and runoff potentials, sensitivity of waters to P inputs, and management practices used for organic and inorganic P sources (Heathwaite et al., 1999; Lemunyon and Gilbert, 1993). The University of Delaware has rated soils with Mehlich 1 STP values $>50 \text{ mg P kg}^{-1}$ as excessive since 1995 and strongly discourages inputs of P from any source (manures, fertilizers, biosolids) if STP is $>100 \text{ mg P kg}^{-1}$. In Arkansas, a Mehlich 3 STP value of 150 mg P kg^{-1} has been proposed as a "good indicator that P

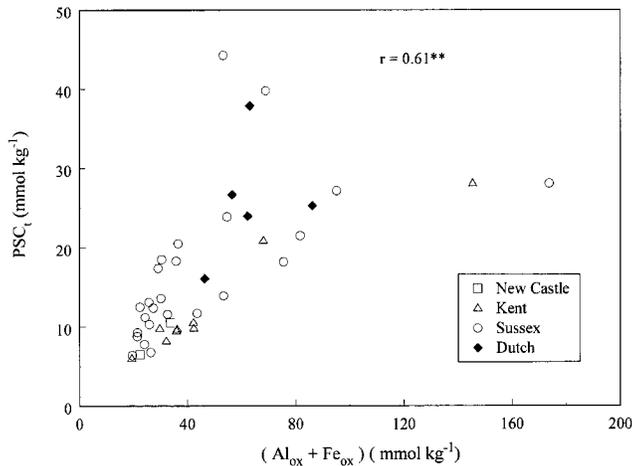


Fig. 4. Relationships between total P sorption capacity ($PSC_t = PSC_r + P_{ox}$) and oxalate-extractable [Al + Fe] for the 41 subset soils.

build-up in the soil is a valid environmental concern” (Daniels et al., 1998; note that Mehlich 3 P $\cong 1.5$ to $2 \times$ Mehlich 1 P; Sims, 1989).

We grouped our data for total P, soluble P, desorbable P, and DPS_{ox} for all 127 soils into the current soil test categories used by the University of Delaware. As shown in Table 2, 24% of the samples were in the low-medium categories, 18% were in the optimum category, and 58% were excessive in STP. By way of comparison, the most recent summary of STP values in Delaware showed that 17% were low-medium, 28% were optimum, and 55% were excessive in P (Sims and Vadas, 1997). In Sussex County, site of Delaware’s geographically dense poultry industry, 65% of the soils tested were rated as excessive in P. Note that the categories used in Delaware are consistent with those used in the Mid-Atlantic and Northeast states (Beegle et al., 1998; Sims, 1998). In our study, as would be expected, soils rated as excessive in P had higher mean values for soluble P, desorbable P, total sorbed P (P_{ox}), DPS_{ox} , and total P than soils in the optimum, medium, and low STP categories (Table 2). However, we also observed that as STP values increased from low to excessive, the more labile forms of P increased relatively more than total P. For example, total P values in the excessive category were ≈ 1.4 times as great as total P in the agronomically optimum STP range. In contrast, soluble P, strip P, STP, and DPS_{ox} were 10.7, 2.7, 3.8, and 2.7 times higher, respectively, in the excessive STP range than in the optimum range. This means that the percentage of total P in soluble, desorbable, and total sorbed (P_{ox}) forms is increasing as soils become excessive in STP due to over-application of P in fertilizers or manures (Table 2). For example, the percentage of total P that could be desorbed by Fe oxide-strips increased from 1% in the low STP to 13% in the excessive STP category, and the percentage of total P extracted by oxalate increased from 21 to 70% (Table 2). This suggests that not only will soils rated as excessive by an agronomic soil test or as *highly saturated* by a DPS measurement have higher concentrations of soluble and desorbable P, but they

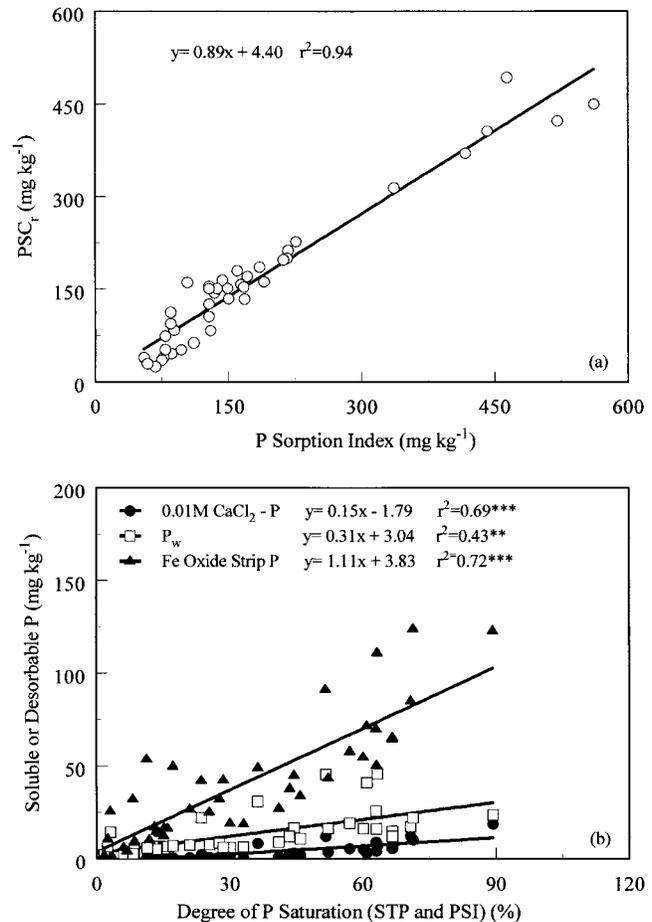


Fig. 5. Relationships, for the 41 subset soils, between (a) a single-point P sorption index (PSI) and PSC_r , and (b) the degree of P saturation (calculated as the ratio of STP to the sum of [PSI + STP]) and 0.01 M $CaCl_2$ -soluble P, P_w , and Fe oxide-strip P.

will have a proportionately larger pool of labile P than soils in the optimum or lower STP categories. Soils with higher percentages of total P in soluble or easily released forms will also presumably have a greater potential to release P into runoff waters or into surface waters following erosion of P-rich particles. Based on long-term desorption studies, Lookman et al. (1995a) reported that “all oxalate extractable P is assumed to be revers-

Table 2. Mean values for selected soil P parameters as a function of soil test rating scale used by the University of Delaware.

Parameter‡	Soil test category†			
	Low	Medium	Optimum	Excessive
Number of samples	10	21	23	73
Mehlich 1 P, $mg\ kg^{-1}$	9	18	36	136
0.01 M $CaCl_2$ -P, $mg\ kg^{-1}$	0.14	0.23	0.39	4.2
Strip P, $mg\ kg^{-1}$	2	10	19	52
P_{ox} , $mg\ kg^{-1}$	79	133	153	400
Total P, $mg\ kg^{-1}$	373	483	411	571
DPS_{ox} , %	6	8	13	35
Strip P/total P, %	1	2	5	13
Mehlich 1 P/total P, %	2	4	9	24
P_{ox} /total P, %	21	28	37	70

† The following soil test (Mehlich 1) P values are used by the University of Delaware for each soil test rating category: Low: 0 to 12 $mg\ kg^{-1}$; Medium: 13 to 24 $mg\ kg^{-1}$; Optimum: 25 to 50 $mg\ kg^{-1}$; Excessive: $>50\ mg\ kg^{-1}$.

‡ Values in table based on all 127 soils.

ibly fixed," and several studies have shown strong correlations between Fe oxide-strip P and *biologically available* or *algal-available* P in soils and runoff (Sharpley et al., 1994).

CONCLUSIONS

Environmental concerns about the degradation of surface water quality by soil P are a major challenge facing agriculture today, especially in areas of highly concentrated animal production where long-term applications of manures to cropland often increase STP to agronomically excessive values (i.e., to values where there will be little or no increase in crop yield due to the input of P in fertilizers or manures). Our results confirm that when hydrologic settings, cropping systems, and nutrient management practices are reasonably similar, increasing STP values above the agronomically optimum range will increase the potential for nonpoint-source pollution of surface waters. Our data show that the risk of P loss to waters by erosion, runoff, or leaching becomes greater because near-linear increases in soluble, easily desorbable, and total sorbed P occur as STP increases and soils become more saturated with P. We also found that soils in the excessive STP category had higher percentages of total P in more labile forms (soluble, desorbable) than soils in the agronomically optimum or lower STP categories. Finally, we observed that the size of the fast desorbing pool of soil P increased as soils become increasingly saturated with P and as P sorption capacity decreased. This supports the use of P saturation testing methods that measure not only the quantity of P present in a soil but the capacity of soils to retain additional P.

One of our objectives was to determine if current soil testing practices can be used to identify fields, farms, and watersheds where nonpoint-source pollution by P is a significant environmental issue. Clearly, soil P testing alone will be inadequate to predict P loss from soil to water because it does not provide direct information on other factors that affect the transport of P to surface waters (e.g., hydrology, topography, nutrient management practices). However, it seems equally apparent that agronomic soil P tests will be useful predictors of other parameters related to the potential for P loss to water, such as soluble P, desorbable P, and the degree of P saturation. For example, the current STP value (Mehlich 1 soil test) used in Delaware to rate soils as agronomically excessive is 50 mg P kg^{-1} , which, based on our data (Fig. 3d) corresponds to a DPS_{ox} value of $\approx 25\%$, in the range of DPS_{ox} values now used for water quality protection in the Netherlands and Belgium (25–40%). Comparison with Dutch standards seems reasonable, given the similar trends we observed in our study between Delaware and Dutch soils. Therefore, the use of existing agronomic STP databases to assist in the initial prioritization of management efforts to reduce nonpoint-source pollution of ground and surface waters by P seems justified. Soil testing laboratories should also consider adopting P saturation tests to improve

their ability to identify soils with greater potential to release P into runoff or leaching waters.

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