An Environmental Threshold for Degree of Phosphorus Saturation in Sandy Soils

V. D. Nair,* K. M. Portier, D. A. Graetz, and M. L. Walker

ABSTRACT

There is critical need for a practical indicator to assess the potential for phosphorus (P) movement from a given site to surface waters, either via surface runoff or subsurface drainage. The degree of phosphorus saturation (DPS), which relates a measure of P already adsorbed by a soil to its P adsorption capacity, could be a good indicator of that soil's P release capability. Our primary objective was to find a suitable analytical protocol for determining DPS and to examine the possibility of defining a threshold DPS value for Florida's sandy soils. Four farmer-owned dairy sprayfields were selected within the Suwannee River basin and soil profiles were randomly obtained from each site, as well as from adjacent unimpacted sites. The soil samples were divided either by horizon or depth, and DPS was determined for each soil sample using ammonium-oxalate (DPS_{Ox}), Mehlich-1 (DPS_{M1}), and Mehlich-3 (DPS_{M3}) extracts. All methods of DPS calculations were linearly related to one another ($r^2 > 0.94$). Relationships between water-soluble P and DPS indicate that the respective change points are: DPS_{Ox} = 20%, DPS_{M1} = 20%, and DPS_{M3} = 16%. These relationships include samples from Ap, E, and Bt horizons, and various combinations thereof, suggesting that DPS values can be used as predictors of P loss from a soil irrespective of the depth of the soil within a profile. Taking into consideration the change points, confidence intervals, agronomic soil test values, and DPS values from other studies, we suggest replacing Mehlich-1 P values in the Florida P Index with the three DPS categories (DPS_{M1} = <30, 30–60, and >60%) to assign different P loss ratings in the P Index.

Sandy soils in the Suwannee River basin of northern Florida have little ability to adsorb P, and yet many dairies in the Suwannee River basin routinely apply P-rich lagoon effluent onto permanent sprayfields for waste disposal and nutrient recycling. Increased P loading to these sites may lead to P loss through runoff and subsurface drainage, contributing to surface water quality degradation. Improved P management of these fields requires the evaluation of soil P concentrations relative to the soil's ability to adsorb P.

Recent studies suggest that the DPS, which relates ammonium oxalate–extractable P to the sum of oxalate-extractable Fe and Al (DPS_{Ox}), is a good indicator of a soil's potential to release P (Hooda et al., 2000). This concept was first introduced in the Netherlands, where it has been shown that P concentrations in the soil solution can exceed a critical concentration well before the soil is completely saturated with P (Breeuwsma and Silva, 1992). This critical concentration is determined by local conditions and generally reflects local surface water criteria for P. The Netherlands has established a water quality goal for ground water of 0.15 mg total P L^{-1}, and their studies have shown that leaching of P could occur especially from manure-contaminated soils (Breeuwsma et al., 1995). In the Netherlands, soils with DPS_{Ox} of >25% were identified as contributing to ground water pollution with P (Breeuwsma et al., 1995). They calculated DPS_{Ox} as $[(Ox\text{-}P)/0.5(Ox\text{-}Fe + Ox\text{-}Al)] \times 100$ where P, Fe, and Al were measured in an oxalate extract.

Oxalate extraction is not frequently performed in soil test laboratories in Florida (Nair and Graetz, 2002) or in other parts of the USA (Sims et al., 2002) due to practical difficulties in the measurement of parameters in the DPS calculations. More common soil tests include Mehlich-1 and Mehlich-3 extractions. The use of these routine agronomic soil tests to calculate DPS would simplify the measurement of DPS, and provide a more accessible analytical tool for P management.

The objectives of this study were to (i) calculate the DPS for manure-impacted and unimpacted sandy soils using ammonium-oxalate (DPS_{Ox}), Mehlich-1 (DPS_{M1}), and Mehlich-3 (DPS_{M3}) extractions; (ii) determine the relationship between DPS_{Ox} and DPS_{M1} and DPS_{M3}; (iii) evaluate the relationship between water-soluble phosphorus (WSP) (assessed using either deionized water or 0.01 *M* $CaCl_2$) and each method of DPS calculation; and (iv) examine the possibility of defining a threshold DPS value for Florida's sandy soils.

MATERIALS AND METHODS

Study Site

The Suwannee River basin was selected for this study. Many of the dairies found in the middle Suwannee River basin, proximal to the Suwannee and Santa Fe Rivers, are situated atop a geomorphic zone classified as the Chiefland Limestone Plain. The upper surface of the aquifer system is relatively close to the surface and layers above it are thin and unconfined (Andrews, 1992). The surficial aquifer system is largely recharged by rainfall that percolates downward through the loose surficial clastic sediments. Water naturally discharges from the aquifer through evaporation, transpiration, spring flow, and downward seepage into the underlying Floridan aquifer system. Phosphorus, nitrogen, and other surface-applied

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Abbreviations: DPS, degree of phosphorus saturation; DPS_{M1}, degree of phosphorus saturation calculated as $[M1\text{-}P/0.5(M1\text{-}Fe + M1\text{-}Al)] \times 100$; DPS_{M3}, degree of phosphorus saturation calculated as $[M3\text{-}P/0.5(M3\text{-}Fe + M3\text{-}Al)] \times 100$; DPS_{Ox}, degree of phosphorus saturation calculated as $[Ox\text{-}P/0.5(Ox\text{-}Fe + Ox\text{-}Al)] \times 100$; M1-Al, M1-Fe, and M1-P, Mehlich 1–extractable aluminum, iron, and phosphorus, respectively; M3-Al, M3-Fe, and M3-P, Mehlich 3–extractable aluminum, iron, and phosphorus, respectively; Ox-Al, Ox-Fe, and Ox-P, oxalate-extractable aluminum, iron, and phosphorus, respectively; STP, soil test phosphorus; WSP, water-soluble phosphorus.

material with leaching potential can move vertically through the soil profile and then both vertically and laterally in the surficial aquifer system.

The middle Suwannee River basin is approximately 25 km long by 25 km wide at the widest point, covering an area of about 1.3 million hectares. The dominant soils of the basin are Entisols, such as Penney (thermic, uncoated Typic Quartzipsamments), Kershaw (thermic, uncoated Typic Quartzipsamments), Ortega (thermic, uncoated Typic Quartzipsamments), or Ridgewood (thermic, uncoated Aquic Quartzipsamments); Ultisols such as Blanton (loamy, siliceous, thermic Grossarenic Paleudults); or Alfisols such as Otela (loamy, siliceous, thermic Grossarenic Paleudalfs) (Soil Survey Staff, 1999). Cropping systems within the sprayfields include rotations of corn (*Zea mays* L.)–perennial peanut (*Arachis hypogaea* L.)–rye (*Secale cereale* L.), bermudagrass [*Cynodon dactylon* (L.) Pers.]–rye, perennial peanut–rye, corn–bermudagrass–rye, corn–sorghum [*Sorghum bicolor* (L.) Moench]–rye, as well as sole crops such as bermudagrass or ryegrass (*Lolium perenne* L.).

Soil Sampling

Soil samples from each horizon within a 0- to 2-m profile were collected from manure-impacted sites on four farmer-owned dairy sprayfields and from adjacent unimpacted sites in the middle Suwannee River basin using a 5-cm-diameter auger. A total of 57 soil profiles were collected from the manure-impacted sites, and 12 profiles were collected from adjacent unimpacted sites of similar soil types. The soil profile locations (a minimum of three each) were selected to represent different vegetation types and management practices (such as irrigation levels) within the manure-impacted sites. The soil samples were collected either by depth or by horizon, depending on the nature of the soil profile. If the depth of any horizon was >25 cm, then that horizon was subdivided and two or more samples were obtained from the horizon. All samples were air-dried and passed through a 2-mm sieve.

For Dairy 1, the depths sampled were: 1 = 0 to 36 cm, 2 = 36 to 51 cm, 3 = 51 to 71 cm, 4 = 71 to 97 cm, and 5 = 97 to 122 cm. Dairies 2, 3, and 4 were sampled by horizon, with each horizon being associated with a different depth increment. For these three dairies, the sampling depth was at least 2 m and, whenever possible, sampling included part of the underlying Bt horizon. Some typical soil profiles were Ap, E1, E2, E3, E4, and E5 (no Bt within the surface 2-m depth); or Ap, E1, E2, E3, E/Bt, and Bt or various combinations of these horizons up to 2 m in depth.

Soil Characterization

Soil pH was determined using a 1:2 soil and water suspension. Oxalate-extractable Al (Ox-Al), Fe (Ox-Fe), and P (Ox-P) were determined by extraction with 0.1 *M* oxalic acid + 0.175 *M* ammonium oxalate (pH = 3.0) (McKeague and Day, 1966). The suspension was equilibrated for 4 h in the dark with continuous shaking, centrifuged, filtered through a 0.45-μm filter, and analyzed for Al, Fe, and P. Mehlich 1, or double acid–extractable (0.0125 *M* H_2SO_4 + 0.05 *M* HCl) P (M1-P), Fe (M1-Fe), and Al (M1-Al) were obtained using a 1:4 soil to double acid ratio (Mehlich, 1953). Mehlich-3 extractions for determination of P (M3-P), Fe (M3-Fe), and Al (M3-Al) were performed as proposed by Mehlich (1984). All metals and P in the Mehlich-1 and oxalate solutions were determined using inductively coupled argon plasma spectroscopy (Thermo Jarrel Ash ICAP 61E; Thermo Elemental, Franklin, MA).

Water-soluble P was determined by extracting each soil sample with water at a 1:10 soil to water ratio for 1 h, and determining P on the filtrate collected after passing through a 0.45-μm filter. The $CaCl_2$–extractable P was also measured using the suggested method for animal manure (Self-Davis et al., 2000), using a 1:10 soil to 0.01 *M* $CaCl_2$ solution. Total P was determined by ashing 1.0 g of soil for 2 h at 823 K, and then solubilizing with 6 *M* HCl (Anderson, 1976). Water-soluble P and total P concentrations were determined by an autoanalyzer (USEPA, 1983; Method 365-1) by the Murphy and Riley (1962) procedure. Total C and N contents of the air-dried samples were determined by an automated combustion procedure using a CNS Analyzer (Carlo Erba, Milan, Italy).

Calculation of the Degree of Phosphorus Saturation

The following methods of calculation were adopted:

$$DPS_{Ox} = [(Ox\text{-}P)/\alpha(Ox\text{-}Fe + Ox\text{-}Al)] \times 100$$

$$DPS_{M1} = [(M1\text{-}P)/\alpha(M1\text{-}Fe + M1\text{-}Al)] \times 100$$

$$DPS_{M3} = [(M3\text{-}P)/\alpha(M3\text{-}Fe + M3\text{-}Al)] \times 100$$

where α is an empirical factor that compares different soils with respect to P saturation. The value of α for the current studies was taken as 0.50 (Beauchemin and Simard, 1999; Breeuwsma and Silva, 1992; Koopmans et al., 2003; Schoumans, 2000; Sims et al., 2002). The α value was close to the value of 0.55 for Spodosols in Florida (Nair and Graetz, 2002).

Statistical Analysis

Mean concentrations were computed for each variable by dairy and impact status. Concentrations for all horizons below the surface horizon were averaged for Dairies 2 through 4 and unimpacted sites to produce a subsurface concentration. Comparisons between surface and subsurface average concentrations were made using general linear models for impacted and unimpacted sites separately due to large differences in residual variances. Comparisons between impacted and unimpacted average concentrations were used to simply indicate trends and hence two-sample *t* tests assuming unequal variances were used.

The relationship between DPS and WSP was modeled as a segmented line (Eq. [1]), with parameters estimated using nonlinear least squares. The change point (d_0) in the fitted segmented-line model was directly estimated. To ensure that the two line segments joined at the change point, the slope of the left-hand line is estimated as a function of the change point and other model parameters (Eq. [2]). Standard errors were estimated from the Fisher information matrix and confidence intervals are constructed using these standard errors and an appropriate *t* distribution critical value. Computations were performed in SAS (SAS Institute, 2001) using a NLIN procedure.

$$WSP = \begin{cases} a_0 + b_0 DPS & DPS \le d_0 \\ a_1 + b_1 DPS & DPS > d_0 \end{cases} \quad [1]$$

$$b_0 = \frac{(a_1 - a_0) + b_1 d_0}{d_0} \quad [2]$$

RESULTS AND DISCUSSION

Soil Characterization

Texture analysis of selected soil samples (n = 37) representative of all horizons gave mean values of 96% sand, 2% silt, and 2% clay (data not shown). Some

Table 1. Mean values for selected chemical characteristics† of the soils from four dairy sprayfields and two unimpacted sites.

Dairy‡	pH	M1-Ca	M1-Mg	M1-Al	M1-Fe	Ox-Al	Ox-Fe	Total C	Total N
		mg kg^{-1}						g kg^{-1}	
				Impacted					
Dairy 1, Depth 1	6.27	894	90	316	23	830	480	7.8	0.9
Dairy 1, Depth 2	6.09	161	27	229	20	730	419	2.8	2.0
Dairy 1, Depth 3	5.75	94	19	179	17	609	397	2.2	ND§
Dairy 1, Depth 4	5.51	69	16	151	15	498	361	2.1	ND
Dairy 1, Depth 5	5.35	54	15	130	12	452	342	1.6	ND
Dairy 2, surface	6.67	1282	68	229	13	494	351	11.0	1.9
Dairy 2, subsurface¶	6.62	159	22	104	11	264	223	2.2	0.6
Dairy 3, surface	7.05	822	56	193	20	376	346	1.6	0.2
Dairy 3, subsurface	5.50	93	10	120	12	304	262	4.4	0.5
Dairy 4, surface	6.67	872	53	158	8	288	283	5.1	ND
Dairy 4, subsurface	6.93	135	10	85	8	212	195	2.0	0.2
				Unimpacted					
Unimpacted 1, surface	3.94	75	9	306	47	776	364	1.5	ND
Unimpacted 1, subsurface	4.23	12	2	209	12	561	257	6.0	0.7
Unimpacted 2, surface	4.65	132	10	137	41	282	387	1.8	ND
Unimpacted 2, subsurface	5.26	384	11	165	24	473	356	4.5	0.3

† M1-Ca, Mg, Al, and Fe, Mehlich 1–extractable calcium, magnesium, aluminum, and iron, respectively; Ox-Al and Fe, oxalate-extractable aluminum and iron, respectively.
‡ Depth 1 = 0 to 36 cm, 2 = 36 to 51 cm, 3 = 51 to 71 cm, 4 = 71 to 97 cm, and 5 = 97 to 122 cm.
§ ND, below the detection limit (0.2 g N kg^{-1}).
¶ Subsurface indicates that all horizons were considered together below the surface (Ap) horizon.

chemical properties of the soils used for this study are presented in Table 1. For Dairy 1, the various chemical properties for the subsurface soils were averaged by depth since the depths for all soil profiles were identical. For the other three dairies, mean values of chemical properties (Table 1) for all horizons below Ap were considered together although the samples were analyzed separately. However, extraction values from individual soil samples were used in the calculation of threshold DPS values. Our intention was not to evaluate depth distribution of DPS in these soil profiles, but to determine whether DPS in subsurface samples (irrespective of horizon type) could be related to WSP as well.

The sum of Ox-Al and Ox-Fe provides an indicator of the sorption capacity of an acid soil (Breeuwsma and Silva, 1992; Nair et al., 1998). The surface soils in this study had Ox-Al + Ox-Fe values ranging from 15 to 40 mmol kg^{-1} compared with the range of values for Dutch agricultural soils of 50 to 110 mmol kg^{-1} (Schoumans and Groenendijk, 2000). For 465 soils in Delaware, Sims et al. (2002) reported mean Ox-Al + Ox-Fe values of 52.5 mmol kg^{-1} with a median value of 37.6 mmol kg^{-1}. Thus, the surface sandy soils of the Suwannee River basin would probably have poorer adsorbing capacities than the sandy soils of the Netherlands and comparable or poorer adsorbing capacity than the soils of the Mid-Atlantic coastal plain. Florida soils were formed from coastal plain (mainly marine) pre-weathered sediments dominated by quartz sand and low in sources of Fe and Al (Brown et al., 1990).

The pH values of manure-impacted soils were invariably higher than for unimpacted soils, with high Ca and/or Mg concentrations being typical of dairy manure–impacted soils (Nair et al., 1995). Calcium and Mg concentrations were significantly higher in the subsurface horizons compared with the surface horizons for impacted soils ($P < 0.01$ using all data after accounting for site differences in overall mean concentrations) suggesting manure constituent movement through the soil profile. Total C concentrations in the soil samples were variable, with a tendency toward higher values in the manure-impacted compared with the unimpacted soils at the surface ($P = 0.04$) but less so at the subsurface ($P = 0.055$) (Table 1). Total N concentrations were below detection limits at several of the sites (Table 1).

Mean values for all P parameters (WSP, M1-P, M3-P, and Ox-P; Table 2) indicate higher concentrations in the surface horizons compared with the subsurface horizons ($P < 0.01$ for all data adjusted for overall site average levels). The concentrations for a given soil vary as M3-P > Ox-P > M1-P > WSP. Concentrations of WSP, M1-P, M3-P, and Ox-P for Dairy 1 all decrease with depth ($P <$

Table 2. Mean values for water-soluble phosphorus (WSP), Mehlich 1–extractable phosphorus (M1-P), Mehlich 3–extractable phosphorus (M3-P), and oxalate-extractable phosphorus (Ox-P) for the soils from four dairy sprayfields and two unimpacted sites.

Dairy†	WSP	M1-P	M3-P	Ox-P
	mg kg^{-1}			
	Impacted			
Dairy 1, Depth 1	15.1	242	412	397
Dairy 1, Depth 2	4.4	63	158	149
Dairy 1, Depth 3	2.0	30	92	90
Dairy 1, Depth 4	1.1	19	63	64
Dairy 1, Depth 5	0.6	12	44	49
Dairy 2, surface	19.6	255	370	357
Dairy 2, subsurface‡	4.8	44	74	71
Dairy 3, surface	13.7	149	236	224
Dairy 3, subsurface	2.6	28	55	60
Dairy 4, surface	11.3	168	246	205
Dairy 4, subsurface	1.9	19	39	42
	Unimpacted			
Unimpacted 1, surface	0.9	28	82	98
Unimpacted 1, subsurface	0.4	13	46	48
Unimpacted 2, surface	1.9	11	33	47
Unimpacted 2, subsurface	1.7	16	13	32

† Depth 1 = 0 to 36 cm, 2 = 36 to 51 cm, 3 = 51 to 71 cm, 4 = 71 to 97 cm, and 5 = 97 to 122 cm.
‡ Subsurface indicates that all horizons were considered together below the surface (Ap) horizon.

Table 3. Relationships among the various methods of degree of phosphorus saturation (DPS)† calculations (DPS_{M1} and DPS_{Ox}, DPS_{M3} and DPS_{Ox}, DPS_{M1} and DPS_{M3}).

Relationship	*n*	r^2
$DPS_{M1} = 2.03(DPS_{Ox}) - 12.5$	405	0.94***
$DPS_{M3} = 1.31(DPS_{Ox}) - 8.2$	405	0.97***
$DPS_{M1} = 1.53(DPS_{M3}) - 0.88$	405	0.95***

*** Significant at the 0.001 probability level

† DPS_{M1}, degree of phosphorus saturation calculated as [M1-P/0.5(M1-Fe + M1-Al)] × 100; DPS_{M3}, degree of phosphorus saturation calculated as [M3-P/0.5(M3-Fe + M3-Al)] × 100; DPS_{Ox}, degree of phosphorus saturation calculated as [Ox-P/0.5(Ox-Fe + Ox-Al)] × 100, where M1-Al, M1-Fe, and M1-P are Mehlich 1–extractable aluminum, iron, and phosphorus, respectively; M3-Al, M3-Fe, and M3-P are Mehlich 3–extractable aluminum, iron, and phosphorus, respectively; and Ox-Al, Ox-Fe, and Ox-P are ammonium oxalate–extractable aluminum, iron, and phosphorus, respectively.

0.001, trend confirmed using Waller LSD separation). Mehlich-1 P concentration, which is Florida's soil test phosphorus (STP), shows a concentration of 30 mg kg^{-1} at a 51- to 71-cm depth, indicating that the soil has P concentrations at this depth that are above the agronomic critical level (Kidder et al., 2002).

Analytical Protocol for Degree of Phosphorus Saturation Calculations

Relationships among the various methods of DPS calculations were linear with r^2 values of >0.94 (Table 3). These relationships suggest that Mehlich-1 and Mehlich-3 solutions can be used for calculation of DPS in states where they are used routinely for agronomic soil tests. The DPS_{Ox} involves measurements of P, Fe, and Al in an oxalate solution. In Florida, and in many parts of the USA, institutional and private laboratories may not always have the facilities to measure these parameters. The oxalate extraction method requires extraction in the dark and measurements of the elements in the solution within a week (Schoumans, 2000), making it difficult to perform the analyses on a routine basis. On the other hand, Mehlich 1 is the current soil test P in Florida and conducting a couple of additional analyses in the extract such as Fe and Al is not a major problem. Further, the time involved in Mehlich-1 extraction is short (5 min) compared with the 4-h extraction time for

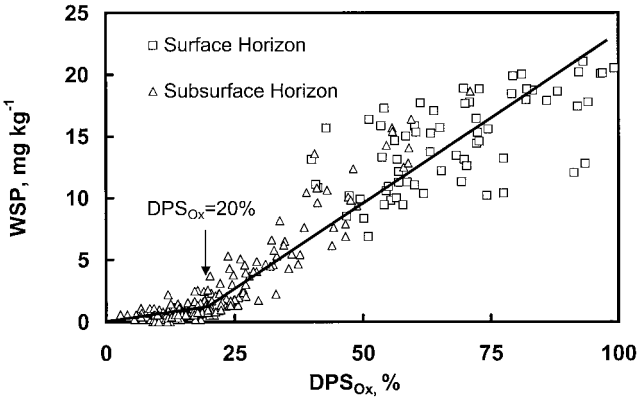

Fig. 1. Relationship between the concentration of water-soluble phosphorus (WSP) and the degree of P saturation calculated using an oxalate extraction (DPS_{Ox}) for manure-impacted surface and subsurface soils from the middle Suwannee River basin.

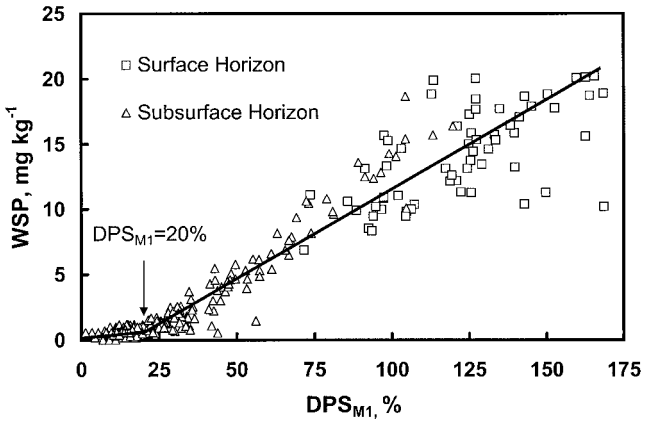

Fig. 2. Relationship between the concentration of water-soluble phosphorus (WSP) and the degree of P saturation calculated using a Mehlich-1 extraction (DPS_{M1}) for manure-impacted surface and subsurface soils from the middle Suwannee River basin.

oxalate extractions. Mehlich 3 is widely used as a soil test P in the Mid-Atlantic states (Sims et al., 2002), so we included calculations of DPS from Mehlich-3 analyses. Knowing the relationships between the three methods of DPS calculations would allow DPS data conversion of comparable soils (e.g., sandy Entisols, Ultisols, or Alfisols) from DPS determinations conducted in most analytical laboratories (soil test solutions) to information available from research laboratories (oxalate solutions).

Relationship between Water-Soluble Phosphorus (Deionized Water or 0.01 *M* $CaCl_2$) and Degree of Phosphorus Saturation

Relationships between water-soluble P (deionized water) and DPS, calculated as DPS_{Ox} (Fig. 1), DPS_{M1} (Fig. 2), and DPS_{M3} (Fig. 3), each gave a "change point." A change point DPS value may be defined as that value above which there is a rapid increase in WSP and therefore a likelihood of a negative impact of P in the soil on water quality. For DPS_{Ox}, the change point is at 20% (95% confidence limits: 17–24%); for DPS_{M1}, the change point is at

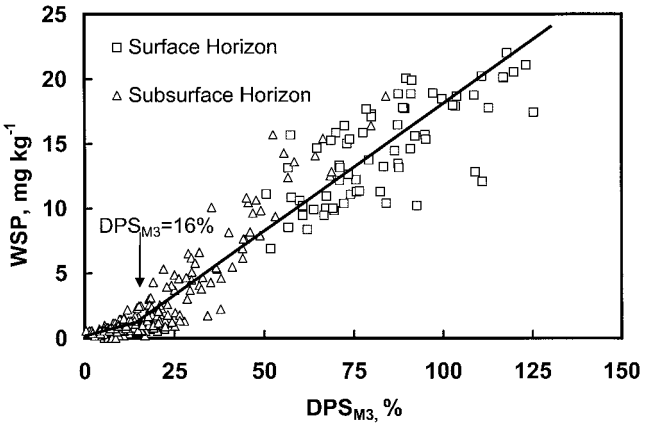

Fig. 3. Relationship between the concentration of water-soluble phosphorus (WSP) and the degree of P saturation calculated using a Mehlich-3 extraction (DPS_{M3}) for manure-impacted surface and subsurface soils from the middle Suwannee River basin.

Table 4. Parameter estimates (with standard errors in parentheses) and R^2 values for the fitted nonlinear relationship models.

Model	Fitted equation	R^2
Oxalate	$WSP = -0.231_{(0.536)} + 0.071_{(0.037)}DPS;\ DPS \le 20.15_{(1.79)}$ $WSP = -4.245_{(0.319)} + 0.272_{(0.007)}DPS;\ DPS > 20.15_{(1.79)}$	0.88***
Mehlich 1	$WSP = 0.228_{(0.613)} + 0.028_{(0.046)}DPS;\ DPS \le 19.84_{(4.89)}$ $WSP = -1.567_{(0.260)} + 0.119_{(0.003)}DPS;\ DPS > 19.84_{(4.89)}$	0.85***
Mehlich 3	$WSP = 0.122_{(0.353)} + 0.060_{(0.035)}DPS;\ DPS \le 16.36_{(2.32)}$ $WSP = -2.196_{(0.244)} + 0.201_{(0.004)}DPS;\ DPS > 16.36_{(2.32)}$	0.91***

*** Significant at the 0.001 probability level.

20% (95% confidence limits: 10–29%); and for DPS_{M3}, the change point is at 16% (95% confidence limits: 11–21%). Parameter estimates including standard errors and R^2 values for the fitted nonlinear relationship models are given in Table 4. Soil samples from all soil horizons, including the upper part of the Bt horizon, were included in the calculations to determine the relationships. Separating the surface and subsurface soils to determine the change point gave almost identical change points by the three methods of DPS determinations. Thus, a measure of DPS can be used to predict the potential for P release from surface soils or from soils at any depth within a profile. All surface soils in the manure-impacted sprayfields have WSP concentrations greater than the change points calculated using any one of the three methods of DPS calculations. Several of the subsurface soils are also above the change points (Fig. 1, 2, and 3), suggesting P movement throughout the soil profile. Mean DPS values for unimpacted soils for all horizons were DPS_{Ox} = 18%, DPS_{M1} = 18%, and DPS_{M3} = 16%, all at or below the respective change points.

The DPS_{Ox} is closely related to P concentrations in leachate waters (Leinweber et al., 1999; Maguire and Sims, 2002), suggesting that DPS_{Ox} can be a suitable tool for predicting subsurface P losses. Nair and Graetz (2002) showed that DPS_{M1} can be used as an indicator of soluble P for both surface A horizons and subsurface Bh (spodic) horizons of Spodosols from the Lake Okeechobee basin. Soils with DPS_{Ox} of >25% contributed to ground water pollution by P in the Netherlands (Breeuwsma et al., 1995). The 25% value corresponds to the Netherlands water quality goal of 0.15 mg total P L^{-1} for ground water P concentrations. No similar comparisons are available for our studies. Values for DPS_{Ox} of >30% in topsoils have been shown to be a threat to water quality degradation in Mid-Atlantic U.S. soils (Paulter and Sims, 2000), and also to be associated with P losses in runoff (Pote et al., 1996).

Maguire and Sims (2002) defined the Mehlich-3 P saturation ratio (M3-PSR) as the ratio between Mehlich-3 P and the sum of Mehlich 3–extractable Fe and Al. Conversion of M3-PSR in their studies (range of 0.10–0.15) to DPS_{M3} (expressed as a percentage) requires introducing a factor of 200 into their equation. The resulting DPS_{M3} is 20 to 30%. The range slightly exceeds our DPS_{M3} change point of 16% (95% confidence limits: 11–21%). The range of DPS_{M3} calculated for the soils used by Maguire and Sims (2002) corresponds to 30 to 45% DPS_{M1} using the conversion equation in Table 3. This information was also used in our selection of threshold ranges for Florida soils.

We also calculated change points using 0.01 *M* $CaCl_2$ solution (Table 5) because $CaCl_2$ extraction has been shown to be a useful P leaching indicator (McDowell and Sharpley, 2001). Change points were detected (Table 5), but they were higher than those values obtained using deionized water. The range among DPS values calculated using the different methods was greater using the $CaCl_2$ extraction (26–38%) compared with the water extraction (16–20%). Maguire and Sims (2002) and McDowell and Sharpley (2001) reported that $CaCl_2$–P concentrations were generally less than WSP concentrations. Mean $CaCl_2$–P concentrations in our studies were only one-third of the mean WSP concentrations.

The Agronomic Soil Test Factor for Setting Environmental Phosphorus Limits

Mehlich-1 P is the agronomic soil test P currently used in Florida, and it is appropriate to relate the soil test to environmental parameters such as the DPS. In Florida, Mehlich-1 P values above 30 mg kg^{-1} are considered high from an agronomic standpoint and a value above 60 mg kg^{-1} is considered very high (Kidder et al., 2002). The University of Delaware has rated soils with Mehlich-1 P values of >50 mg P kg^{-1} as excessive (Paulter and Sims, 2000). We therefore examined corresponding DPS_{Ox} values for these Mehlich-1 P concentrations. A Mehlich-1 P concentration of 30 mg P kg^{-1} corresponds to a DPS_{Ox} value of 22%, whereas a 60 mg P kg^{-1} value corresponds to a DPS_{Ox} value of 28% (Fig. 4). These values agree well with the DPS_{Ox} value of 25% corresponding to 50 mg P kg^{-1} (Paulter and Sims, 2000). Paulter and Sims (2000) used an α value of 0.68 in their equation to calculate DPS whereas we used a value of 0.50. Given the empirical nature of α, we included the factor in our calculations, primarily for comparison with DPS_{Ox} values that have been used in recent literature.

Table 5. Change points and their confidence intervals for DPS_{Ox}, DPS_{M1}, and DPS_{M3} using 0.01 *M* $CaCl_2$–P instead of water-soluble P.

Parameter†	Change point	95% Confidence intervals
	%	
DPS_{Ox}	28	24–31
DPS_{M1}	38	30–45
DPS_{M3}	26	21–31

† DPS_{M1}, degree of phosphorus saturation calculated as [M1-P/0.5(M1-Fe + M1-Al)] × 100; DPS_{M3}, degree of phosphorus saturation calculated as [M3-P/0.5(M3-Fe + M3-Al)] × 100; DPS_{Ox}, degree of phosphorus saturation calculated as [Ox-P/0.5(Ox-Fe + Ox-Al)] × 100, where M1-Al, M1-Fe, and M1-P are Mehlich 1–extractable aluminum, iron, and phosphorus, respectively; M3-Al, M3-Fe, and M3-P are Mehlich 3–extractable aluminum, iron, and phosphorus, respectively; and Ox-Al, Ox-Fe, and Ox-P are ammonium oxalate–extractable aluminum, iron, and phosphorus, respectively.

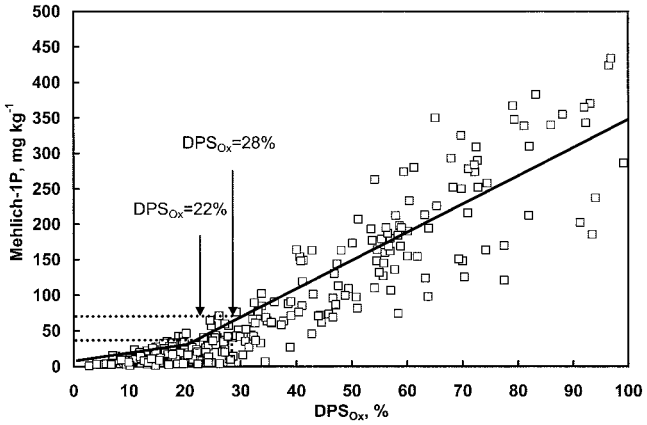

Fig. 4. Relationship between Mehlich-1 P and the degree of P saturation calculated using an oxalate extraction (DPS_{ox}) for manure-impacted surface and subsurface soils from the middle Suwannee River basin. Horizontal dotted lines indicate agronomic high (30 mg P kg^{-1}) and very high (60 mg P kg^{-1}) soil test P concentrations in Florida (Kidder et al., 2002).

The α value for Spodosols of the Lake Okeechobee basin in Florida is 0.55 (Nair and Graetz, 2002), which is close to the 0.5 value used in the current studies.

A Threshold Degree of Phosphorus Saturation Value for Florida's Sandy Soils

Based on the change points, confidence intervals, and agronomic soil test values measured herein, we recommend a threshold DPS_{M1} of 30% for Florida sands. Values for DPS_{M1} of 31 to 60% warrant caution with regard to further addition of P to a land-use system, and DPS_{M1} values of >60% suggest soils as contributors to water quality impairment. While these ranges are arbitrary, they are useful as indicators of P loss potential from agricultural systems. The suggested ranges may be subjected to changes based on added field and laboratory information. The recommended threshold value of 30% is above agronomic fertility requirements (Fig. 4), and further P additions to the soils are unnecessary for plant growth. This threshold value of 30% is also comparable with the Netherlands-recommended DPS value of 25% and the calculated DPS_{M1} range between 30 and 45% for the soils Maguire and Sims (2002) used in their studies. Dairy soils from the Suwannee River basin, introduced as a check of our data, fitted the WSP–DPS relationship (Fig. 3) (Nair et al., 2002b). Also, the relationship held for soils of the Okeechobee basin of Florida, in spite of the extremely poor retention capacity of these soils. Therefore, the threshold DPS ranges recommended based on the best professional judgment of the authors were applicable to the Okeechobee soils as well (Nair et al., 2002a).

Maguire and Sims (2002) concluded that an environmental soil limit (such as DPS_{M1}) should be used as an initial indicator of potential water quality problems, with a more detailed scheme, such as the P Index, being used to access the risk of P contamination at any given site. The Florida P Index (http://efotg.nrcs.usda.gov/popmenu3FS.aspx?Fips=12001&MenuName=menuFL.zip; select "Section IV" then "B. Tools" then "Florida Phosphorus Index"; verified 26 June 2003) was developed as a field-based index to assess site conditions and potential P loss vulnerability. The index includes consideration of transport factors such as soil erosion, soil runoff class, leaching potential, and distance from a water course, along with management factors such as STP, P application method, and source and rate of P application. Agronomists often consider STP as an inappropriate factor for evaluating environmental P losses as STP was originally calibrated for agronomic purposes (Sharpley et al., 1999). DeLaune et al. (2002) recently showed that STP is not the most reliable indicator of P in runoff when animal manure (poultry manure) was surface applied to a plot. The relationship between WSP and M1-P was linear in our study, WSP = 0.612(M1-P) + 0.3976; $r^2 = 0.9072$; $n = 405$; $p < 0.001$. Also, WSP was related to Mehlich-3 P as WSP = 0.038(M3-P) − 0.6606; $r^2 = 0.8720$; $n = 405$; $p < 0.001$ (data not shown). No change point could be identified in the WSP relationship with either Mehlich-1 or Mehlich-3 P.

We recommend replacing the STP factor in the Florida P Index with DPS_{M1} for the fertility index value. The three ranges for DPS_{M1} (<30, 30–60, and >60%) would then be assigned different P loss ratings. At present we are considering only surface soil DPS values to replace surface Mehlich-1 P concentrations in the Florida P Index.

The current Florida P Index attempts to incorporate leaching potential based primarily on visual observation of the Bt horizon within a soil profile (Nair and Graetz, 2002). This study shows that DPS can be related to WSP for all soil samples throughout a soil profile, including samples of the Bt horizon. However, it may not be practical for the field evaluator to determine DPS at regular intervals throughout a soil profile during evaluation of the P Index. We are currently evaluating the possibility of incorporating subsurface DPS values into the P Index using simple field tests that could be related to DPS throughout a soil profile.

CONCLUSIONS

Strong correlations exist between DPS_{Ox} and DPS_{M1}, DPS_{M3} and DPS_{M1}, and DPS_{M3} and DPS_{Ox}, indicating that the three methods are equally appropriate for DPS calculations. For the sandy soils of Florida, as well as for parts of the USA where Mehlich-1 P is used routinely as the STP, DPS_{M1} could be a convenient indicator of P loss from an agricultural system. Where Mehlich-3 P is the routine STP, then DPS_{M3} may be the appropriate indicator. Relationships between WSP and DPS for Florida soils support change points of DPS_{Ox} = 20%, DPS_{M1} = 20%, and DPS_{M3} = 16%. The relationships include soils from all horizons (Ap, E, Bt, and various combinations thereof), indicating that DPS values can be related to P loss from a soil irrespective of the depth of the soil within a profile. Various factors employed for the calculation of DPS, including both confidence intervals and agronomic factors, suggest that threshold DPS values should be used with caution. However, a

comprehensive scheme for potential P loss vulnerability, such as a P Index that includes DPS as a factor, appears appropriate.

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