

# Consistency of the Threshold Phosphorus Saturation Ratio across a Wide Geographic Range of Acid Soils

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## Core Ideas

- Establish a common threshold in P saturation across a geographic diversity of soils.
- Predict water-soluble P from soil P storage capacity to guide fertilizer strategies.
- Relate runoff P concentration with soil P storage capacity.

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## ABSTRACT

Loss of legacy soil phosphorus (P) due to historical over-application of fertilizers and manures can result in eutrophication of water bodies. The soil P storage capacity (SPSC) has been proposed as a tool to estimate the capacity of humid region soils to act as either sinks or sources of P to runoff or leaching. The SPSC is based on a threshold molar ratio of extractable P/(Al+Fe), called the soil P saturation ratio (PSR), above which water-soluble P abruptly increases. Objectives were to (i) document consistency of the threshold PSR for a wide geographic range of acid soils, (ii) determine applicability of a SPSC vs. water-soluble P predictive equation to soils from various regions, and (iii) relate SPSC with water quality parameters. Surface samples were collected from acidic, humid-region soils encompassing multiple physiographic provinces of the United States. Water quality data, including dissolved reactive P and total P, were obtained from various study sites. Phosphorus, Fe, and Al in Mehlich 3 solutions were determined, and PSR and SPSC calculated. The threshold PSR based on 186 samples is 0.1, indicating a common threshold across the geographic range of this study. Phosphorus concentrations in runoff related closely with SPSC, PSR, and M3-P values of soils that were the source of the runoff. However, SPSC has the additional potential of estimating extent of legacy P loss at excessive concentrations for soils of eastern and central United States. Results support general applicability of PSR and SPSC for acid soils.

**Abbreviations:** DRP, dissolved reactive phosphorus; ICP-OES, inductively coupled plasma-optical emission spectrometry; M3-Al, Mehlich 3-extractable aluminum; M3-Fe, Mehlich 3-extractable iron; M3-P, Mehlich 3-extractable phosphorus; PSR, phosphorus saturation ratio; SPSC, soil phosphorus storage capacity; STP, soil test phosphorus; TP, total phosphorus.

Global phosphate reserves are finite (Jasinski, 2015; Dhillon et al., 2017), even as excess P application to land has resulted in soil P levels surplus to crop needs (i.e., *legacy P*; Sharpley et al., 2013). The loss of legacy soil P (i.e., excess P already in the soil irrespective of the P source) from agricultural fields to water bodies can have deleterious ecological consequences in addition to constituting the waste of a vital resource (Kleinman et al., 2015). Approaches are, therefore, needed to accurately assess legacy P and ultimately to minimize its accumulation and environmental impact. A relationship that normalizes extractable P to extractable (Fe+Al) for sandy soils was first introduced in the Netherlands (van der Zee and van Riemsdijk, 1988; Breeuwsma et al., 1995), but has been extended to other parts of the world. The original method of calculation for this relationship specified oxalate-extractable P, Fe, and Al (Breeuwsma et al., 1995; Koopmans et al., 2004). Modifications to the concept, the P saturation ratio (PSR), are based on soil test P (STP) used in various parts of the United States. Mehlich 1 extracts (Beck et al., 2004; Nair et al., 2004) and Mehlich 3 extracts (Maguire and Sims, 2002; Sims et al., 2002; Nair et al., 2004) have been shown to be suitable to calculate the PSR for soils of the southeastern United States (Nair, 2014).

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The utility of the PSR stems from a “change point,” or threshold value that it exhibits, above which water-soluble P (surrogate for pore water P) abruptly begins to increase. Nair and Harris (2004) used the PSR concept to define the “soil P storage capacity” (SPSC). The SPSC calculation (see “Phosphorus Saturation Ratio and Soil Phosphorus Storage Capacity” section under “Materials and Methods”) amounts to a determination of remaining capacity (as expressed in mg kg<sup>-1</sup>, kg ha<sup>-1</sup>, “furrow slice,” etc.) prior to reaching the PSR threshold and a condition of elevating P loss risk. The SPSC captures the risk of unimpacted soils that have low P sorption capacity whereas STP and PSR do not. For example, Spodosols of the southeastern United States coastal plain generally have 99% uncoated quartz sand in upper horizons and negligible P retention (Harris et al., 1996). A freshly cleared Spodosol field would typically produce an STP measurement of <5 mg kg<sup>-1</sup> suggesting that this location would be suitable for additional P applications in terms of inorganic P or manures based on STP values. However, an SPSC– (capacity-based) assessment would reveal that such a soil would have minimal capacity for safe P storage (i.e., soil would be prone to lose P from the system). It would also signal the need for best management practices (BMPs) that could be adopted for P fertilizer-use efficiency (such as slow-release fertilizers, fertilizer timing, or fertilizer incorporation).

The concept of PSR had been introduced and used to evaluate the potential for a soil to release P via runoff or leaching in the early 2000s (Maguire and Sims, 2002; Sims et al., 2002; Nair et al., 2004). The SPSC concept, has been used in the southeastern United States for various soil management systems (Nair, 2014; Dari et al., 2015). The PSR–SPSC concept has also been shown to be effective in risk assessment of P loss from a groundwater field monitoring site in Delaware (Andres and Sims, 2013). Recently, SPSC has been used in the assessment of subsurface water flow (Dari et al., 2017). The practical use of SPSC has been extended to water-related issues in wetland soils as well (Nair et al., 2015).

The validity of the SPSC is tied directly to the use of a PSR threshold that accurately represents the range of soils being assessed. A discrete PSR threshold has been verified for sandy coastal plain soils of the southeastern United States (Nair, 2014). However, there is uncertainty regarding the geographic range of applicability for this threshold. This study was undertaken with a broad objective of obtaining a threshold PSR value (or values for a group of soils)

across a geographic diversity for soils within the Southern Region/Midwest/Mid-Atlantic areas, focusing on soils for which secondary Fe and Al forms have significant control over P retention. Specific objectives were to (i) obtain the change point (threshold PSR) using P, Fe, and Al extracted via standard soil test procedures; (ii) determine if the SPSC vs. water-soluble P predictive equation developed for Florida soils is applicable to soils from other regions; and (iii) relate SPSC with water quality data obtained at various sites. In general, our approach addresses the applicability of soil P assessment approaches for humid-region soils for which P dynamics are largely controlled by Fe and Al oxides.

## MATERIALS AND METHODS

### Soil Sampling and Sites Description

We sampled surface horizons (~15–25 cm thickness) of a broad range of acidic, humid-region soils for which P retention is primarily controlled by poorly crystalline Fe and Al oxides. Another important consideration was to include soil samples spanning a sufficient range of P loading to ensure an adequate number above and below the PSR threshold. Soils were collected from both plant and animal production systems. Our study included both freshly collected soils as well as archived samples. Geographic diversity was achieved by collecting soil samples from the following groups of regions encompassing multiple physiographic areas of the United States: (i) Northeastern Atlantic Coastal Plain, Piedmont, Valley and Ridge, and Allegheny Plateau; (ii) Ozark Plateau; (iii) Southeastern Piedmont; and (iv) Southern-most Atlantic Coastal Plain and Gulf Coastal Plain. Additional archived samples of slightly to highly weathered soil samples, dominated by non-calcareous (Fe+Al) materials were obtained from various regions in the United States and referred to as soil samples from “various regions” (Table 1).

#### Group 1: Mid-Atlantic United States (Northeastern Atlantic Coastal Plain, Piedmont, Valley and Ridge, and Allegheny Plateau)

Soils sampled within this group include Alfisols, Entisols, and Ultisols. Many of these soils derive from sites with long-term cropping history and water quality monitoring and have contributed to current nutrient management understanding in their respective regions.

**Table 1. Geographic location of the study sites.**

Geographical regions	States	Sites	Samples	Soil order†
Group 1: Mid-Atlantic United States Northeastern Atlantic Coastal Plain Piedmont Valley and Ridge Allegheny Plateau	Maryland, Pennsylvania	21	32	Alfisols, Entisols, and Ultisols
Group 2: Ozark Plateau	Arkansas	1	8	Alfisols and Ultisols
Group 3: Southeastern Piedmont	Georgia	3	36	Ultisols
Group 4: Southern-most Atlantic Coastal Plain Gulf Coastal Plain	Florida, Georgia	5	75	Entisols, Spodosols, and Ultisols
Group 5‡: Various regions	NA§	17	17	Alfisols, Inceptisols, and Ultisols

† Soil orders are in alphabetical order.

‡ Additional details on these soils available in Sharpley et al., 1985.

§ NA, not available.

## Group 2: Ozark Plateau

These soils are Alfisols (Razort silt loam, fine-loamy, mixed, active, mesic Mollic Hapludalfs) and Ultisols (Captina silt loam, fine-silty, siliceous, active, mesic Typic Fragiuudults) from the Ozark Plateaus and Ouachita Province. Soil samples have a history of surface runoff monitoring and records of nutrient management, in terms of fertilizer and manure application timing and rates. Soils were collected from both pasture crop settings. These sites are described in Sharpley et al. (2015).

## Group 3: Southeastern Piedmont

Soils were sampled from long-term cropping system study plots on Ultisols and Alfisols in the state of Georgia (Endale et al., 2010). Soils at these plots, after 14 yr of different tillage (no tillage or conventional tillage) and fertilization treatments (poultry litter or mineral fertilizer), provided a range in P concentrations. Soils were collected from 0.8-ha field-scale watersheds at the College of Agricultural and Environmental Sciences Central Georgia Research and Education Center, located in the Southern Piedmont. A mixture of forage grasses is the dominant vegetation at these locations. Soil series include Altavista (fine-loamy, mixed, semiactive, thermic Aquic Hapludults), Cecil (fine, kaolinitic, thermic Typic Kanhapludults), Helena (fine, mixed, semiactive, thermic Aquic Hapludults), and Sedgelyield (fine, mixed, active, thermic Aquatic Hapludalfs). Six watersheds were fertilized with poultry litter and four have had no fertilizer applied to them since 1995.

## Group 4: Southern-Most Atlantic Coastal Plain and Gulf Coastal Plain

These samples were collected from soils of northern to central Florida (Entisols, Spodosols, and Ultisols). Sampling sites in Florida were located on three University of Florida satellite research facilities: Beef Research Unit (BRU, north-central peninsula), Plant Science Research and Education Unit (PSREU, central-peninsula), and North Florida Research and Education Center (NFREC, panhandle).

## Group 5: Various Regions

Seventeen archived soils from continental United States and Puerto Rico obtained from the USDA Soil Conservation Service (now Natural Resources Conservation Service) National Soil Survey Lab, for which soil characterization data were available (Sharpley et al., 1985), were included in this study. The selected samples were slightly to highly weathered soils represented by the soil orders Alfisols, Inceptisols, and Ultisols.

## Soil and Water Quality

Water quality data, i.e., dissolved reactive P (DRP) and total P (TP), were obtained from three previously monitored sites in University of Maryland (Group 1), one site in Arkansas (Group 2), and six sites in Georgia (Group 3). The DRP data for runoff water collected from these sites were plotted separately with calculated SPSC for the soil samples collected from the same sites at all locations (Groups 1, 2, and 3). Information on soil characteristics and water quality monitoring details is provided in Supplementary Table S1. Phosphorus, Fe, and Al in a Mehlich 3 (M3) solution were determined and SPSC was calculated. Relationships of runoff data with SPSC were evaluated at each of the three locations.

## Group 1

Runoff was collected from research plots in Maryland and Pennsylvania (designated as Maryland, Pennsylvania 1, and Pennsylvania 2), in 2012, 2002, and 2002, respectively, and water quality parameters (DRP and TP) were measured (Supplementary Table S2).

## Group 2

The Harmon site in Arkansas on Captina silt loam had received poultry litter applications at various rates and times during 2009–2015. Soils were collected from seven locations within the site and from an adjacent forested area. Runoff data (DRP and TP) collected at various times during 2009–2015 were available for each of the eight Arkansas locations (Supplementary Table S3). Mean values of runoff (collected each year and averaged over 5 yr) were related to SPSC calculated from M3 P, Fe, and Al.

## Group 3

Runoff was collected from six plots (Plots 1–6) in 1995, 1997, and 2001 from the Eatonton Tom Hall area in Georgia and water quality parameters (DRP and TP) were measured (Supplementary Table S4).

## Chemical Analyses

### Soil Physicochemical Properties Determination

Soil samples were homogenized, air-dried, and passed through a 2-mm sieve before analyses. Soil pH was measured with a suspension of soil in water at a 1:2 (w/v) soil/solution ratio using a glass electrode. Soil textural analyses (percentages of sand, silt, and clay) were determined on representative soil samples from each Group (8, 7, 3, 4, and 3 soil samples from Groups 1, 2, 3, 4, and 5, respectively) using the hydrometer method (Bouyoucos, 1962). Decisions on number of samples from a given group were made based on variability of P-retaining properties of the soils such as (Fe+Al) within each group. Water-soluble P was determined by extracting each soil sample with deionized water at 1:10 (w/v) soil/water ratio, and analyzing P on the filtrate collected after passing through a 0.45- $\mu$ m filter. Water-soluble P was analyzed using an autoanalyzer (USEPA, 1983, Method 365-1) by the Murphy and Riley (1962) procedure.

Soil samples were extracted with M3 extracting solution (0.2 M  $\text{CH}_3\text{COOH}$  + 0.25 M  $\text{NH}_4\text{NO}_3$  + 0.015 M  $\text{NH}_4\text{F}$  + 0.13 M  $\text{HNO}_3$  + 0.001 M EDTA) by shaking a soil–solution suspension for 5 min at a 1:10 soil/solution ratio to determine P (M3-P), Fe (M3-Fe), and Al (M3-Al) (Mehlich, 1984). Soil samples were extracted with a Mehlich 1 (M1) solution (0.0125 M  $\text{H}_2\text{SO}_4$  + 0.05 M HCl) to determine P (M1-P), Fe (M1-Fe), and Al (M1-Al) using a 1:4 soil/M1 solution ratio (Mehlich, 1953). The suspension was equilibrated, centrifuged, filtered through a 0.45- $\mu$ m filter, and analyzed for Fe, Al, and P. All metals and P concentrations in the M1 and M3 solutions were determined using inductively coupled plasma spectroscopy (ICP; Thermo Jarrel Ash; 61E, Franklin, MA).

### Phosphorus Saturation Ratio and Soil Phosphorus Storage Capacity

The PSR of a soil from P, Fe, and Al concentrations was calculated as:

$$\text{PSR} = \frac{\text{Extractable-P} / 31}{(\text{Extractable-Fe} / 56) + (\text{Extractable-Al} / 27)} \quad [1]$$

where extractable P, Fe, and Al are converted to moles (Sims et al., 2002; Nair, 2014). The extracting reagent can be an acid ammonium oxalate extractant or a soil test solution such as M1 or M3. In this study, the PSR has been calculated from M3 extraction data as:

$$PSR = \frac{M3-P/31}{(M3-Fe/56)+(M3-Al/27)} \quad [2]$$

Soil phosphorus storage capacity was calculated using the threshold PSR (see the “Statistical Analyses” section) as:

$$SPSC \text{ (mg kg}^{-1}\text{)} \\ = (\text{Threshold PSR} - \text{Soil PSR}) \\ \times [(M3-Fe/56)+(M3-Al/27)] \times 31 \quad [3]$$

### Statistical Analyses

Empirical relationships between water-soluble P and PSR (and SPSC), and between SPSC and DRP in runoff samples, were statistically obtained using correlation and regression analyses in Excel 2013. A proc nonlinear split line (NLIN) model in SAS 9.3 (SAS Institute, 2010) statistical software was used to determine the change point or threshold PSR as computed by others (McDowell and Sharpley, 2001; Casson et al., 2006; Chakraborty et al., 2011). The model describes linear relationships between water-soluble P and PSR before and after the PSR vs. water-soluble P change point (Nair, 2014).

## RESULTS AND DISCUSSION

### Soil Characterization

Soil textures ranged from loamy to sandy (Table 2). The relative coarseness is likely attributable to the soil samples being from surface (eluvial) horizons. In addition, sand is a prevalent component in soils of the coastal plain of the eastern United States. The higher clay content for soils of Group 3 is likely attributable to the Piedmont parent material and historical erosion. The pH of the soil samples from Groups 1 through 5 were in the acidic range (4.8–5.6). The water-soluble P of the soil samples from study regions varied from 0.2 to 5.0 mg kg<sup>-1</sup>. The M3-P concentrations for Groups 1 to 4 varied from 33 to 106 mg kg<sup>-1</sup>, whereas M1-P values ranged from 16 to 81 mg kg<sup>-1</sup> (Table 2).

### Threshold Phosphorus Saturation Ratio and Water-Soluble Phosphorus

We obtained a statistically determined threshold PSR value of 0.1 (95% confidence interval 0.05 to 0.15;  $p < 0.0001$ ) for the soils from the different regions of this study when M3-P, Fe, and Al were used in the PSR calculations. The water-soluble P concentration increased significantly once the threshold PSR was exceeded, while the slope of the relationship was negligible below the threshold (Fig. 1), as reported earlier for Florida upland (Nair, 2014) and wetland (Nair et al., 2015) soils. Since M3 is the soil test solution for most of the Groups in our study and appears to be applicable to all soils irrespective of the geographic location, the threshold PSR of 0.1 was used in the computation of SPSC. We obtained the threshold PSR for each of the five groups of soils separately (Supplementary Table S5) and confirmed that the threshold for all groups was essentially the same. We also looked into the relationship of water-soluble P to PSR calculated using P, Fe, and Al in a M1 solution and found a discrepancy in the threshold PSR value (Supplementary Fig. S1); so, the relationships were evaluated separately for the Group 3 soils (Supplementary Fig. S2; Samples from Georgia, where M1 is the current soil test).

### Soil Phosphorus Storage Capacity

A linear relationship was obtained between negative SPSC and water-soluble P (Fig. 2), the case for which soils are expected to be a P source. When SPSC was positive, water-soluble P was minimal (Fig. 2), in accordance with the discrete PSR threshold (Fig. 1) and as reported previously (Nair and Harris, 2014). Approximately 65% of the soils of the current study exhibited a negative SPSCs, whereas 35% had a positive SPSC. Soils from Group 5 accounted for most of the positive SPSC. The relationship between SPSC calculated using M3-extracted P, Fe, and Al and values obtained from the same calculation using M1 extraction was linear (Supplementary Fig. S3).

Water-soluble P for the soils collected from different regions used in this study were predicted from the SPSC and water-soluble P relationship developed by Nair and Harris (2014). Predicted values of water-soluble P were compared with water-soluble P values measured in the laboratory from the soils collected during this study. A reasonable relationship ( $R^2 = 0.88$ ) was obtained between measured and predicted water-soluble P data (Fig. 3). This relationship is expected to hold for weathered acidic soils across a broad geographic range within the eastern United States

**Table 2. The mean (and standard deviation) of chemical and physical properties of soils in the present study.**

Soil properties	Group 1†	Group 2	Group 3	Group 4	Group 5
Sand, %	52 (4)	37 (4)	36 (3)	92 (7)	75 (6)
Silt, %	29 (3)	47 (5)	30 (3)	5 (0.2)	16 (2)
Clay, %	19 (3)	16 (1.5)	34 (2)	2 (0.1)	9 (0.6)
Textural class	loam to sandy loam	silt loam	clay loam	sand	sandy loam
pH	4.8 (0.5)	5.2 (0.5)	5.6 (0.6)	5.1 (0.5)	5.2 (0.4)
Water-soluble P, mg kg <sup>-1</sup>	3.0 (0.1)	2.3 (0.1)	1.0 (0.03)	5.0 (0.6)	0.2 (0.03)
Mehlich 3-P, mg kg <sup>-1</sup>	76 (10)	40 (4)	33 (2)	106 (14)	13 (2)
Mehlich 1-P, mg kg <sup>-1</sup>	81 (13)	27 (5)	16 (3)	48 (5)	NA‡

† Group 1, Mid-Atlantic United States (Northeastern Atlantic Coastal Plain, Piedmont, Valley and Ridge, and Allegheny Plateau); Group 2, Ozark Plateau; Group 3, Southeastern Piedmont; Group 4, Southern-most Atlantic Coastal Plain and Gulf Coastal Plain; Group 5, various regions.

‡ NA, not available.

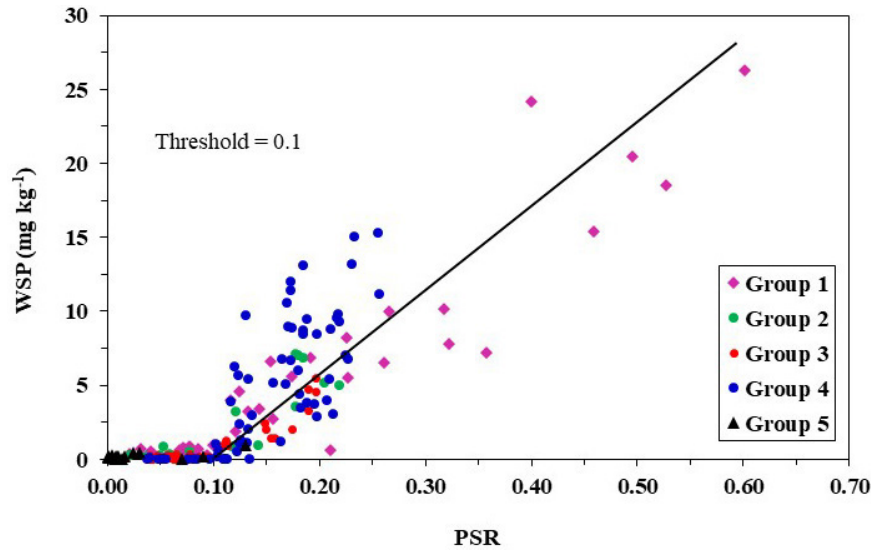


Fig. 1. Relationship between water-soluble P (WSP) and the P saturation ratio (PSR; calculated using P, Fe, and Al extracted in a Mehlich 3 solution) for all soil samples used in the study. Threshold PSR is 0.10; 95% confidence interval = 0.05 to 0.15;  $p < 0.0001$ . Group 1: Mid-Atlantic United States; Group 2: Ozark Plateau; Group 3: Southeastern Piedmont; Group 4: Southern-most Atlantic Coastal Plain and Gulf Coastal Plain; Group 5: Various regions.

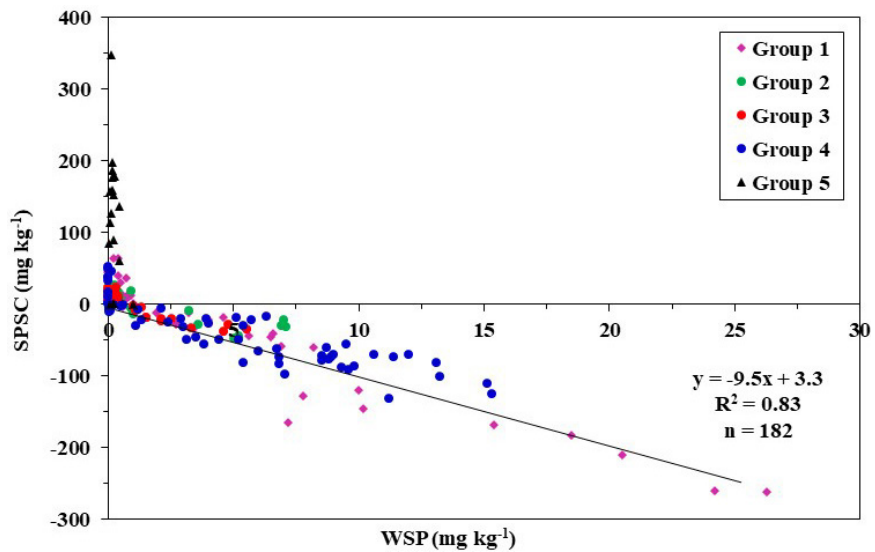


Fig. 2. Relationship between soil P storage capacity (SPSC) and water-soluble P for all soils in this study. The SPSC calculated from P, Fe, and Al in a Mehlich 3 solution. Group 1: Mid-Atlantic United States; Group 2: Ozark Plateau; Group 3: Southeastern Piedmont; Group 4: Southern-most Atlantic Coastal Plain and Gulf Coastal Plain; Group 5: Various regions.

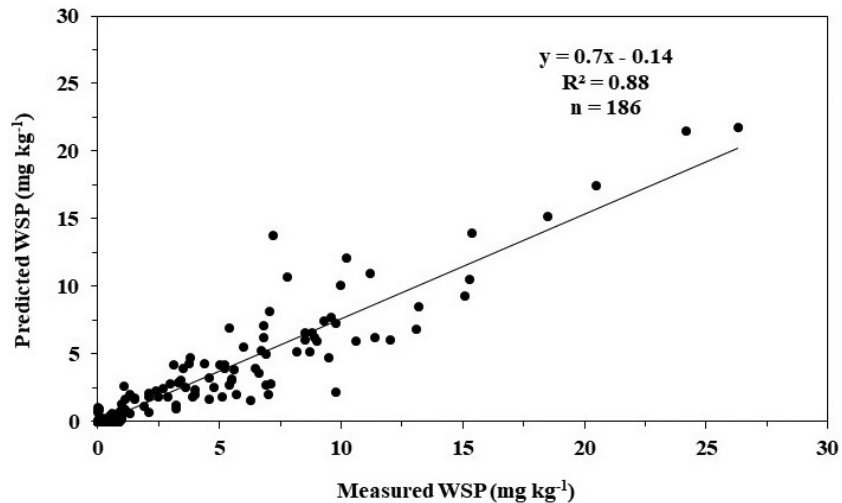


Fig. 3. Relationship between predicted and measured water-soluble P (WSP) for all soils in our current study. We used the SPSC equation (negative values) developed for Florida soils to predict WSP in the current soil samples.

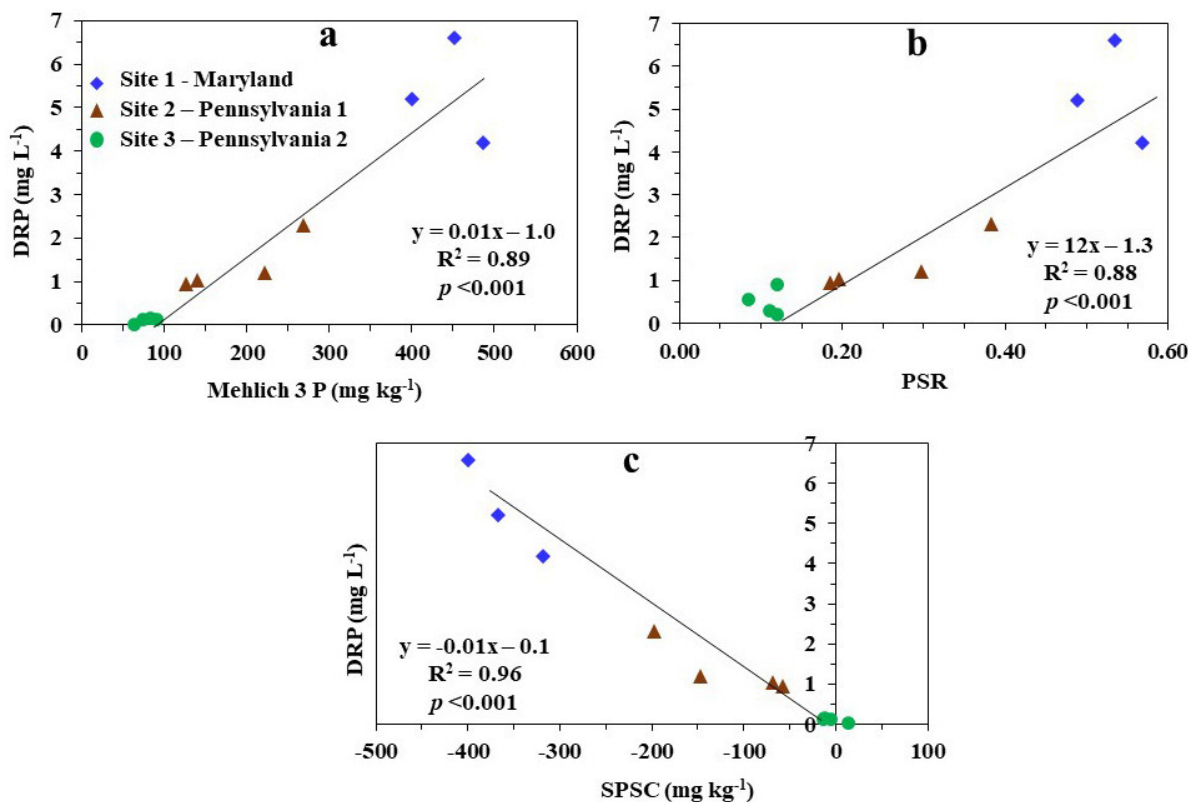


Fig. 4. Relationship of dissolved reactive P (DRP;  $\text{mg L}^{-1}$ ) in runoff water with (a) Mehlich 3-P (M3-P), (b) P saturation ratio (PSR), and (c) soil P storage capacity (SPSC;  $\text{mg kg}^{-1}$ ) calculated using M3-P, Fe, and Al from the soils collected from three sites (Maryland, Pennsylvania 1, and Pennsylvania 2; Group 1). At the Maryland site, each data point is the average DRP in runoff water collected in 5 yr (2007, 2008, 2009, 2010, and 2012) from three different locations; M3-P, PSR, and SPSC were obtained on soil samples collected in 2012. At the Pennsylvania 1 and 2 sites, each data point is the individual DRP measured in runoff water collected from four locations; M3-P, PSR, and SPSC were obtained from the soil samples collected in 2002. The trend-lines in Fig. 4a and 4b exclude the soil sample with PSR below threshold value of 0.1 and positive SPSC (one site from Pennsylvania 2), respectively.

as long as the procedure for water-soluble determination is kept uniform, e.g., soil/solution ratio (Chrysostome et al., 2007).

### Relationship of Soil Phosphorus Storage Capacity to Field Water Quality Data

The relationship between DRP and negative SPSC for all three locations was strong ( $R^2$  values of 0.96, 0.89, and 0.92, respectively, and  $p$  values of  $<0.001$  at all locations) (Fig. 4c, 5c, and 6c). In all cases, DRP was the lowest (minimal) when SPSC was positive or minimally negative. Similarly, strong correlations ( $R^2$  values of 0.97, 0.85, and 0.87 at Group 1, 2, and 3, respectively;  $p$  values  $<0.001$  for all three locations) were obtained between TP measured in runoff and negative SPSC for the soil samples collected from the same sites at all locations (Groups 1, 2, and 3) (Supplementary Table S6). This suggests that SPSC could predict both DRP and TP in runoff at a given site. Site-specific features in soil and landscape characteristics (e.g., slope gradient and length of transport) preclude there being a single relationship applicable to all sites.

Similar trends were obtained when researchers attempted to predict DRP from runoff or leachate water using extractable P only (M1 or M3) (Sharpley et al., 2015; Kleinman et al., 2015; King et al., 2015). We looked into the relationships between DPR and PSR, and M3 (Fig. 4b, 5b, and 6b, and 4a, 5a, and 6a, respectively). These relationships were similar to that of DRP with SPSC. However, the SPSC has an advantage over PSR and STP in that it could be used to predict the amount of P subject to runoff or leaching before concentrations declined to background levels; this amount would differ for soils with the same PSR value based

on the soil's retention capacity. Another advantage of the SPSC over the other P risk indicators is that it can be used to predict the amount of P that can be added to a soil (such as during spray field irrigation) prior to the soil becoming an environmental risk. The absolute value of negative SPSC is an indicator of the extent of P loss risk the soil poses as well as the legacy P that could be mined from soils by cropping systems.

## CONCLUSIONS

It was feasible to obtain a threshold PSR (0.1) applicable across a geographic diversity of acidic soils within the United States and Puerto Rico, as calculated using P, Fe, and Al concentrations from a standard soil test extraction (Mehlich 3). The water-soluble P extracted from these soils can be predicted from SPSC using an equation originally developed in the southeastern coastal plain of the United States. Phosphorus concentrations in runoff correlated strongly with the SPSC values of soils that were the source of the runoff. The PSR, M1-P, and M3-P also related closely with runoff P concentrations. However, SPSC has the additional potential of predicting the extent of P loss at excessive concentrations, i.e., legacy P, in absolute terms (e.g.,  $\text{kg ha}^{-1}$ ).

## Supplemental Material

Supplemental materials include site location details, runoff monitoring data, and additional chemical characterization data, all of which provide background information pertinent to the article. Also included are SPSC calculations based on Mehlich 1 extractions.

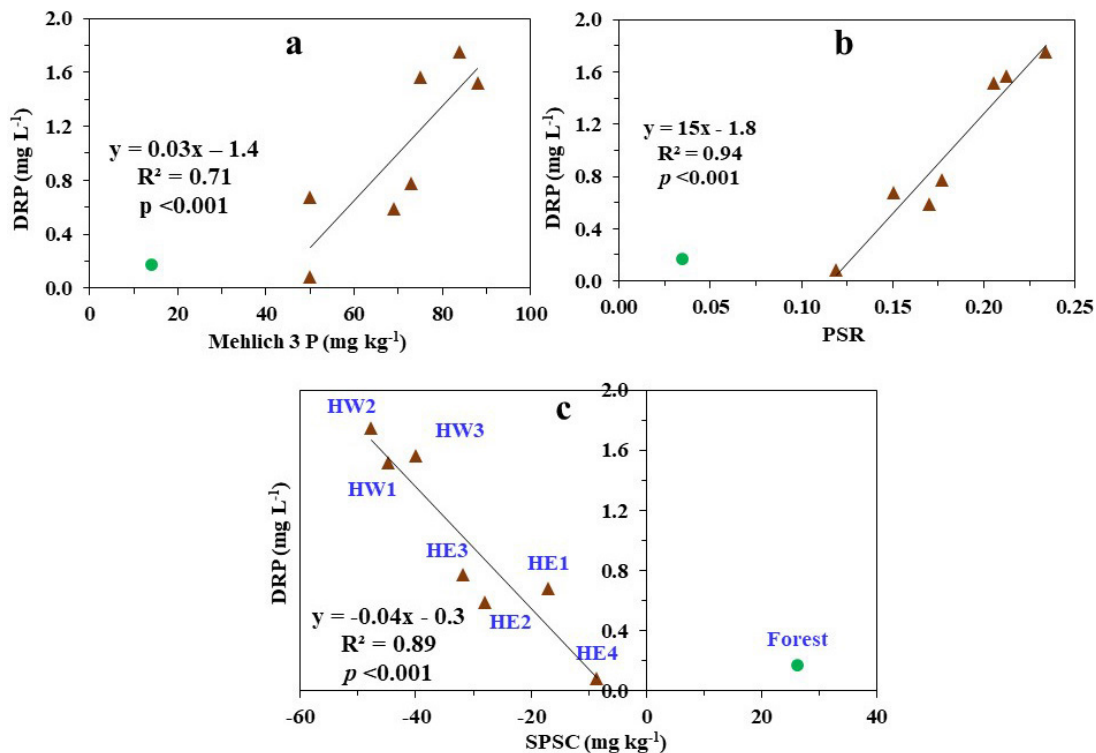


Fig. 5. Relationship of dissolved reactive P ( $\text{mg L}^{-1}$ ) in runoff water to (a) Mehlich 3-P (M3-P), (b) P saturation ratio, and (c) soil P storage capacity ( $\text{mg kg}^{-1}$ ) calculated using M3 extracted P, Fe, and Al from soils collected from eight sites in Arkansas (Group 2). Each data point is the average DRP measured in runoff water in 5 yr (2009, 2010, 2011, 2012, and 2013) collected from Harmon, AR (Forest, HE1, HE2, HE3, HE4, HW1, HW2, and HW3); M3-P, PSR, and SPSC were obtained from the soil samples collected in 2015. Trendlines in Fig. 5a and 5b exclude the soil sample with PSR below threshold value of 0.1 and positive SPSC (Forest site), respectively.

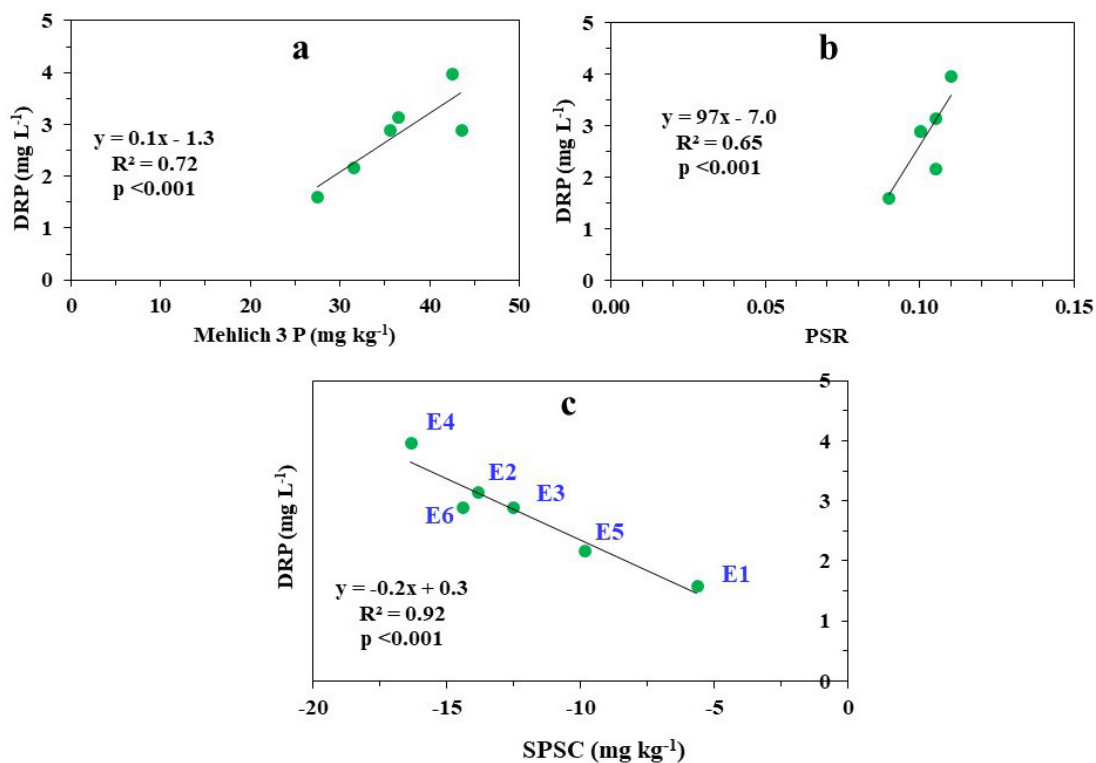


Fig. 6. Relationship of dissolved reactive P ( $\text{mg L}^{-1}$ ) in runoff water from soils collected at the six sites in Georgia (Group 3) with (a) Mehlich 3-P (M3-P), (b) P saturation ratio, and (c) soil P storage capacity ( $\text{mg kg}^{-1}$ ) calculated using M3-P, Fe, and Al. Each data point is the average DRP measured for runoff water in 2 yr (1995 and 1997) from sites E1, E2, E3, E4, E5, and E6; M3-P, PSR, and SPSC were calculated from soils collected in 1995 and 1997 from 12 randomly selected locations within each site. The DRP collected in each year is the average of 12 to 15 data points within each site.

## Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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