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Review Article

Soil Phosphorus Storage Capacity for Environmental Risk Assessment

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Reliable techniques must be developed to predict phosphorus (P) storage and release from soils of uplands, ditches, streams, and wetlands in order to better understand the natural, anthropogenic, and legacy sources of P and their impact on water quality at a field/plot as well as larger scales. A concept called the "safe" soil phosphorus storage capacity (SPSC) that is based on a threshold phosphorus saturation ratio (PSR) has been developed; the PSR is the molar ratio of P to Fe and Al, and SPSC is a PSR-based calculation of the remaining soil P storage capacity that captures risks arising from previous loading as well as inherently low P sorption capacity of a soil. Zero SPSC amounts to a threshold value below which P runoff or leaching risk increases precipitously. In addition to the use of the PSR/SPSC concept for P risk assessment and management, and its ability to predict isotherm parameters such as the Langmuir strength of bonding, K_L, and the equilibrium P concentration, EPC_0, this simple, cost-effective, and quantitative approach has the potential to be used as an agronomic tool for more precise application of P for plant uptake.

1. Introduction

Concern about the environmental fate of phosphorus (P) has arisen from evidence that P derived from land-applied animal wastes and fertilizers can potentially promote eutrophication of water bodies [1–9]. There is a need to develop ways of managing nutrients such that risks to the environment are minimized. This paper describes a field test approach that we call the "soil P storage capacity" (SPSC) which enables the on-site prediction of how much P can be added to a soil prior to development of significant risk of P leaching and/or runoff.

"Soil-test P" (STP) procedures that were initially developed for crop nutrient recommendations have been adapted to environmental risk assessment for P loss [10–13]. Another approach used in P risk assessment involves a "change point" phenomenon, which corresponds to a threshold of P loading where a marked increase in solution P concentration is observed [14]. The change point threshold is expressed in terms of the molar ratio of extractable P to the sum of extractable Al and Fe [14–17]. The latter ratio is called the P saturation ratio (PSR). The PSR can be determined by various extractants, including those used for STP.

The STP and PSR have two shortcomings stemming from failure to capture P retention capacity: (i) a low value is not indicative of a safe application site and (ii) neither provides a means of predicting the "safe lifespan" of an application site. Predictions require that P retention capacity be taken into account and that the remaining capacity (prior to risk of environmentally detrimental P release) be determined. The authors have developed a concept (SPSC) that overcomes the risk assessment limitations of STP and PSR [17].

2. The Soil P Storage Capacity Approach

First, consider the following expression, defined as "soil P storage capacity" (SPSC) SPSC = (threshold PSR-soil PSR) $*$ (sum of extractable Al and Fe in moles) [17], where threshold PSR = PSR value at "change point" as determined regionally [18]; soil PSR = PSR of soil under investigation.

This calculation amounts to a determination of remaining capacity (mg kg^{-1}, kg ha^{-1} "furrow slice", etc.) if the metal extractant exhaustively extracts the metal phases primarily responsible for P sorption [19]. Ammonium oxalate [20] is

the best extractant for this purpose. However, the above SPSC calculation can also be made using STP (e.g., Mehlich 1 or Mehlich 3-P, Fe and Al) via calibration with oxalate extraction because of high correlation between the two procedures [19, 21]. This is an obvious practical advantage.

The SPSC would capture the risk of unimpacted soils that have low P sorption capacity while STP and PSR would not. The concept would be a true P risk indicator for any soil of the population for which the PSR threshold is applicable. Relationship of SPSC to water extractable P shows that as long as SPSC is positive, the soil will not release significant P to solution but will release P at increasing amounts as SPSC becomes increasingly negative (Figure 1, [21]); the relationship is applicable to surface [19] as well as subsurface soil layers [22]. Further, the equilibrium P concentration at zero sorption (EPC_0; the solution P concentration at which the rate of P adsorption equals the rate of desorption) is minimal when SPSC is positive and increases when SPSC becomes negative [23].

Sandy soils of the SE US coastal plain have high infiltration rates and nearly level topography such that vertical flow (leaching) rather than surface runoff is often the prevalent mode of P transport. Leaching in these soils can be accompanied by lateral subsurface flow in the saturated zone. Hence, the environmental fate of P applied to these soils is largely controlled by the P retention characteristics not only of the surface horizon, but also of subsurface horizons extending to the water table. A feasible site-specific means of evaluating the P storage limits prior to leaching risks is needed for manure- and fertilizer-amended soils.

The predominant soil orders in Florida, USA, are Spodosols, Entisols, and Ultisols. The Bh horizons of Spodosols (Alaquods) with organically complexed metals, Bt horizons of Ultisols (Paleudults) with loamy-to-clayey textures, and common subsurface horizons (e.g., E, Bw) of Entisols (Quartzipsamments) with grain coatings, all show discrete thresholds for PSR [21–23]. Based on their respective threshold PSR values, it is possible to calculate the SPSC for subsurface horizons. Chakraborty et al. [24] illustrated how the compositional differences of Alaquods and Paleudults would result in differences in P loss potential between these two prevalent soil great groups as well as seasonal differences in P loss for Alaquods. An SPSC assessment of subsurface horizons enables determination of the absolute amount of P that the horizon could hold prior to releasing the P at environmentally unacceptable limits. The Chakraborty et al. [22] study further illustrated that information on SPSC of the Bh horizon and the horizons overlying the Bh are pertinent to water table management. For example, maintaining a water table above the upper Bh boundary when the Bh has significant SPSC would short-circuit the potential to reduce off-site movement of P. Their results also showed that even when there is an abundance of crystalline components that contribute to P sorption above the threshold PSR, the most tenaciously bound P is associated with noncrystalline metal oxides such as those extracted by an oxalate or a soil test solution such as Mehlich 1 or Mehlich 3. Therefore, the PSR concept appears applicable to a wide range of soil types and not just sandy soils or soils with inorganically complexed Al.

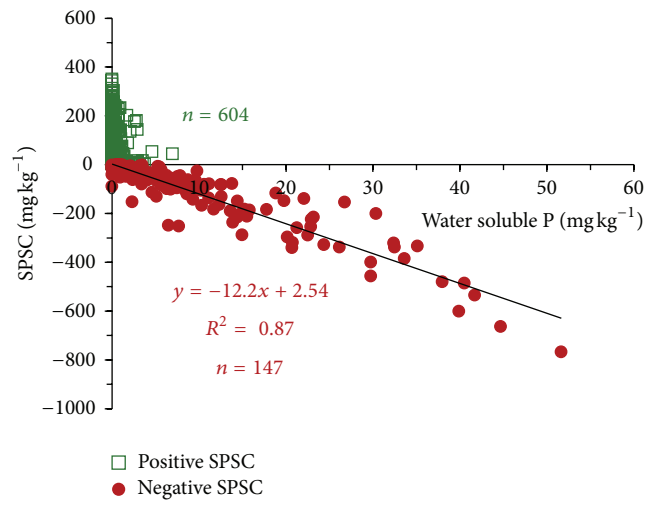


Figure 1: Relationship between soil P storage capacity (SPSC) and water soluble P for A and E horizons of manure-impacted soils. Source: Nair et al. [21].

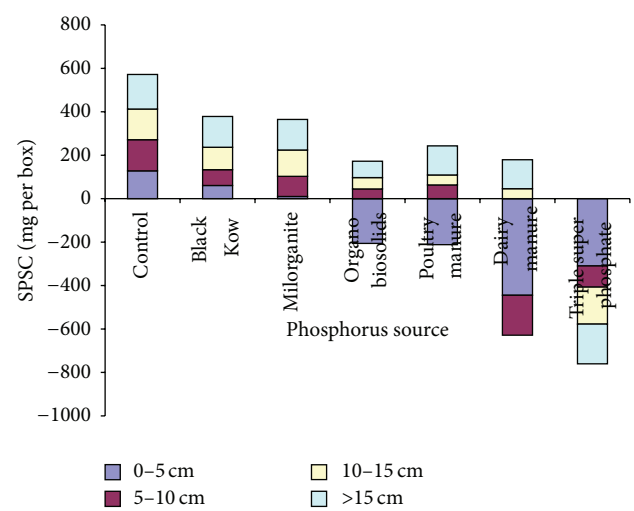
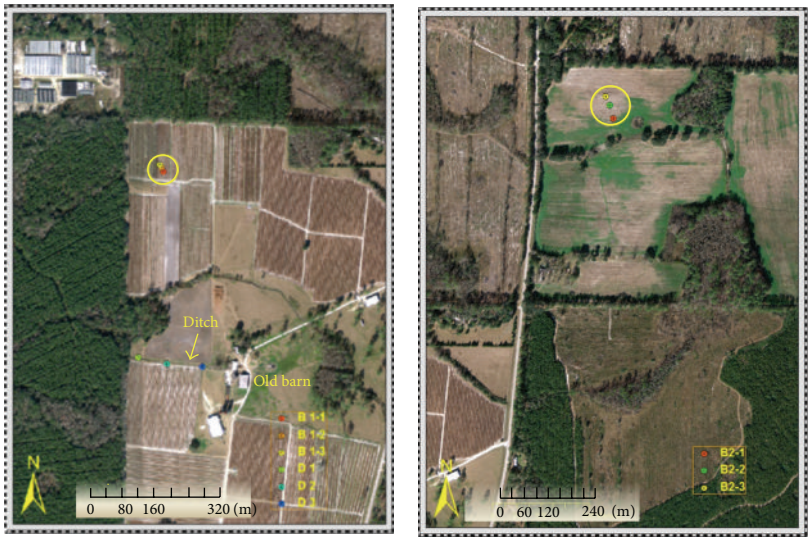


Figure 2: Soil phosphorus storage capacity (SPSC) differences by depth for various P sources Black Kow compost, Milorganite biosolid, Orlando biosolid, poultry and dairy manure, and inorganic fertilizer (triple superphosphate) applied at the same total P concentrations (9 g per box), compared to the control with no P additions in a laboratory rainfall simulation experiment. Source: Rew et al. [28].

The SPSC approach also has potential to provide an assessment of environmental limits for natural and constructed wetlands. A similar relationship as in Figure 1 was shown by Nair et al. [25] for data from uplands and wetlands of eight beef ranches within the Lake Okeechobee Basin, Florida. Further, the authors also indicated that wetlands are not eternal sinks for P and there is a potential for P to move down a soil profile for wetland soils as well. The SPSC concept would also be useful in determining whether a site is suitable for establishing a constructed wetland for facilitating P removal from an impacted farm or ranch. If the SPSC of a potential site is negative, then it will not be suitable for



Location	Horizon	Depth (cm)	SPSC (mg/kg)
B1-1	Ap	0–20	−23
	Bh1	30–35	−147
B1-2	Ap	0–20	−20
	Bh1	40–45	−109
B1-3	Ap	0–20	−35
	Bh1	30–35	−169
D1	Ap	0–40	25
	Bt	80+	32
D2	Ap	0–40	−39
	Bh	60–75	−30
D3	Ap	0–40	−1100
	Bt	120+	8

(a)

Location	Horizon	Depth (cm)	SPSC (mg/kg)
B2-1	Ap	0–20	−13
	Bt	60+	38
B2-2	Ap	0–20	13
	Bt	60+	23
B2-3	Ap	0–20	46
	Bt	50+	36

(b)

Figure 3: Sites B1 (a) and B2 (b) of a blueberry farm are operated by the same landowner. Random soil samples were collected from Site B1 (B1-1, B1-2, and B1-3) (as clustered in the NW corner of the field, away from the barn area, within a radius of ~20 m) and Site B2 (B2-1, B2-2, and B2-3) (as clustered in the N-central part of the field, within a radius of ~30 m). Samples were also collected across a ditch, D1, D2, and D3 at Site B1 with D1 closest to the forested area and D3 closest to the old barn. Soils were collected and analyzed by S. Haile, D. Chakraborty, and J. Showalter.

constructing the wetland. It would also be possible to estimate the time it would take for storing additional P prior to the soil becoming a P source.

3. Application of the SPSC Concept for Environmental Risk Assessment

3.1. Phosphorus Source Effects. Another factor that needs to be accounted for in P risk assessment is the P source itself. Not all P sources have the same potential to release P. In effect, simply knowing the total P applied is not sufficient to predict the nature of P movement off-site. The P retention mechanisms are markedly different for manure- and commercial-fertilizer-amended sandy soils. Differences relate in large part to the nature of P forms in manures, which are mainly inorganic but less soluble than typical commercial fertilizers. Distinctions have implications for long- versus short-term P release as well as mitigation approaches.

Laboratory-scale rainfall simulation studies are often used as a means for evaluating potential P loss from a soil; for example, Eghball et al. [26] studied the effects of long-term fertilizer and manure applications on P and N transport in runoff and suggested avoiding applications when there is a probability for rain immediately following applications. Phosphorus concentrations in rainfall simulation leachate on a laboratory scale study (Table 1) illustrate substantial differences in leachate concentrations depending on the P source [27]. The data show that leaching was significantly less for manure sources than for a commercial fertilizer and most of the other sources tested.

Differences in SPSC for various P sources applied at the same total P concentrations (at a rate of 300 kg^{-1} ha or 9 g per "box," dimensions: 100 cm × 30 cm × 20 cm) in the laboratory scale study are illustrated in Figure 2 [28]. The 20 cm depth rainfall simulation "box" was divided into four segments at the end of the simulation studies and SPSC calculated for each segment. The soil in the study was from the A horizon of a Spodosol with minimal P retention capacity. The control (no amendment) had the maximum storage capacity (positive SPSC for all segments) while SPSC was completely exhausted for the soil amended with inorganic fertilizer (triple superphosphate). Dairy manure-impacted

Table 1: Phosphorus concentrations in rainfall simulation† leachates for each P source for three simulations conducted at 1-week intervals.

P source	Leachate P, mg L^{-1}		
	Simulation 1	Simulation 2	Simulation 3
Inorganic P commercial fertilizer	38	227	107
Dairy manure	3	3	4
Black Kow compost	4	38	5
Milorganite biosolid	1	10	2
Orlando biosolid	26	16	15
Poultry manure	8	8	7
Control	1	1	1

†Developed along guidelines proposed by the National P project. Source: [27].

soil had some remaining capacity at the lower soil depths. The high negative SPSC in the surface 0–5 cm depth indicates that the P will continue to be released slowly over time with additional rainfall application.

3.2. Legacy Phosphorus and Water Quality. Legacy phosphorus is the P that has accumulated in the soil over a period of time, and its continuous release from the soil affects water quality even when external P loads are minimized or eliminated. Sharpley et al. [29] have pointed out that legacy P "makes it difficult to distinguish the effects of current conservation measures from historical land management." The SPSC is the only available tool that captures P storage from historical land uses without the need for any prior P-application records.

3.2.1. Differing P Loss from Identically Managed Agricultural Sites. Two sites in close proximity to each other owned by the same farmer were evaluated for P storage. The sites were used for blueberry production and the farmer managed them identically. However, the quality of water leaving the first site (B1) negatively impacted an adjacent water body.

Three soil profiles were collected by horizon at both of the sites, B1 and B2. In addition, three soil profiles were collected from a ditch (D1, D2, and D3) leaving the first site and draining to a lake through a forested area (Figure 3). The SPSC for all soil profiles for B1 was negative; only the surface (A horizon) and the more retentive subsurface horizon (Bh or Bt) were considered in the evaluation. The ditch sample closest to an old barn showed the highest negative SPSC (−1100 mg kg^{-1}) and SPSC values increased at distances away from the barn. Even at this heavily P-impacted location, there appears to be some P storage left at the high P-retentive Bt horizon at a depth of 120 cm. The old barn area represents an example of legacy P where the manure P is continuously released when in contact with water [30], and this release could continue for a long period of time, perhaps even centuries. Loss of P from this site may not be via the ditch alone, but also through subsurface flow across the whole site. Locations within B2, though under similar management as B1, have mostly positive SPSC such that additional fertilization would likely be needed for sustainable crop production.

Table 2: Soil phosphorus storage capacity (SPSC) of selected dairy and beef soil profiles to 120 cm depth.

Location	Component	Impact level†	Depth to Bh (cm)	SPSC (kg ha^{-1})
		Active		
Dairy 1	Native	Very low	51	3560
Beef 1	Native	Very low	91	730
Dairy 1	Forage	Low	30	2480
Beef 2	Pasture	Low	81	1710
Dairy 2	Pasture	Low	28	11870
Dairy 3	Holding	High	132	−5320
Dairy 4	Holding	High	99	620
Dairy 2	Holding	High	36	4280
Dairy 1	Intensive	High	41	950
		Abandoned		
Dairy 5	Holding	High	117	−36390
Dairy 6	Intensive	High	56	−9670
Dairy 6	Intensive	High	58	−2200
Dairy 6	Intensive	High	84	−24400
Dairy 7	Intensive	High	79	−22880

†The P-impact levels were classified based on the total P (TP) concentration in an earlier study [30]. The intensive component (small area closest to the barn) and the holding component (larger area where the cattle are fed and held overnight) had the highest P loading, and the pasture component (both dairy and beef pastures that are areas used for grazing) and the forage component (forage production area) had lower total P. Native areas are not significantly affected by human activities and represent minimal background conditions.

3.2.2. Legacy Phosphorus and Water Table Management. Here we consider two dairy locations on Spodosols with differing P-impact levels (Figure 4). The first is a minimally P-impacted pasture location on Myakka fine sand (sandy, siliceous, hyperthermic Aeric Alaquod) and the other is a heavily P-impacted soil on Pomello fine sand (sandy, siliceous, hyperthermic Oxyaquic Alorthod). At both locations, soil samples were collected to 120 cm depth. The pasture on Myakka has considerable P storage capacity at and below the Bh horizon. On the other hand, the cattle holding area near the barn on Pomello fine sands does not have a P retentive horizon to 120 cm depth and all depths above 120 cm have negative SPSC and therefore constitute a source of P loss. Under these conditions, raising the water table to a meter depth would not be problematic for the pasture soil, but the risk of losing P from the heavy P-impacted area would be substantial. Raising the water table above the Bh (e.g., to 25 cm depth) of the pasture soil would also present problems in the fact that the only retentive layer (Bh) could be bypassed by lateral movement in the minimally retentive E horizon. Others have documented an association between negative SPSC and elevated solution P both in the field (pore water [31]) and laboratory (column leachates [19]).

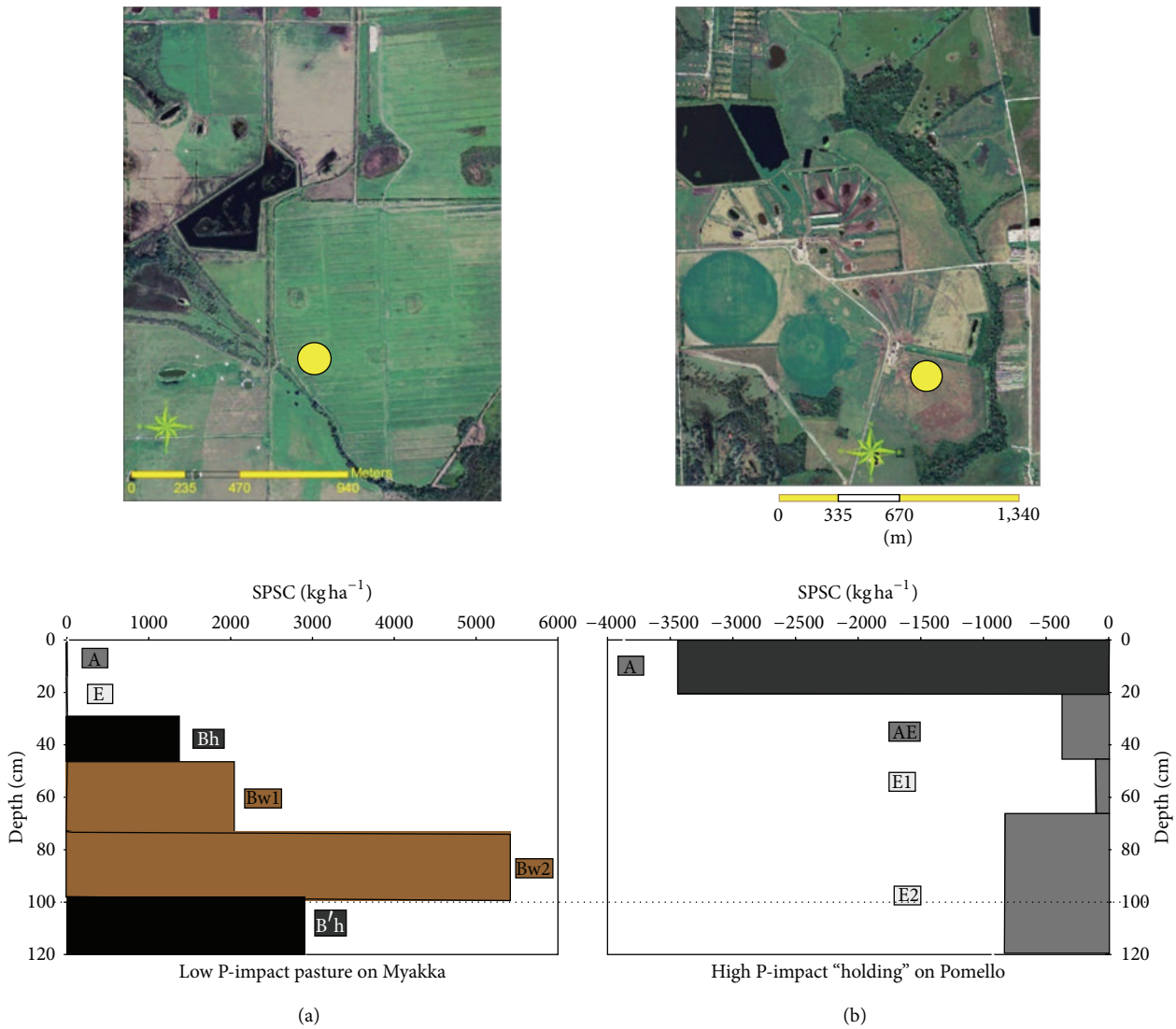


Figure 4: Water table management in two soils with different P-impact levels. On the left is a low P-impact pasture on a Myakka soil series with the Bh at approximately 30 cm depth. On the right is a heavily P-impacted cattle holding area on a Pomello soil without any Bh horizon to a depth of 120 cm. A hypothetical water table represented by a dotted line is at a 100 cm depth. Data was compiled by M. Chrysostome and the GIS maps generated by S. Haile.

3.2.3. Phosphorus Storage to 120 cm Depth in Active and Abandoned Dairy Soils. Since manure-impacted soils are prone to continuous P losses via either horizontal or vertical P movement, it follows that P will continue to be lost from a soil even after a dairy is abandoned (no longer operational). The negative effects of legacy P have been illustrated in an earlier example in this section. The SPSC enables tracking of P movement in any P-impacted soil; examples of SPSC to 120 cm in soil profiles of differing P input in active and abandoned dairies are illustrated in Table 2. The SPSC values are additive and hence a single value can be obtained for a soil profile to any desired depth, in this case to 120 cm.

The depth to the P-retentive Bh horizon is an important factor in the vertical movement of P. Among the active dairy locations selected, only one soil has the Bh horizon below the 120 cm depth (Table 2). This is the only soil profile among the active dairies where the SPSC to a 120 cm depth is negative irrespective of the P-impact level. The abandoned dairies selected were all heavily manure-impacted and the SPSC is negative for the soil profile to a 120 cm depth. The Bh horizon of these abandoned dairies was all within the 120 cm depth considered, suggesting that P movement from these abandoned dairies had compromised even the Bh horizon with high P-retentive capacity. An important conclusion from this observation is that remedial measures must be taken to confine the releasable P soon after the dairy is no longer in operation.

3.3. SPSC under Different Land Uses. Random soil samples were collected to a 40 cm depth to evaluate the potential for the use of the SPSC concept across a watershed (Figure 5, [32]) with different land uses. The land uses

Table 3: Selected soil characteristics† of wetland and ditch soil samples collected to a depth of at least 1 m. Source: [34].

Profile#	Depth cm	LOI %	WSP	TP	M1-P mg kg^{-1}	M1-Al	M1-Fe	PSR‡	SPSC¶ mg kg^{-1}
Wetland soil	0–10	6.73	45.1	328	124.8	57	6	1.80	−153
	10–20	4.41	93.1	327	327.2	70	8	3.86	−414
	20–50	1.84	35.5	64	39.3	16	3	1.91	−48
	50–125	1.55	9.3	31	21.0	7	2	2.29	−26
	125–170	3.11	ND	173	16.7	1142	9	0.01	149
Ditch soil	0–10	10.94	59.5	213	73.0	37	2	1.67	−89
	10–20	13.36	59.5	205	219.0	68	3	2.73	−274
	20–50	0.43	8.1	37	26.6	13	2	1.69	−33
	50–65	1.46	12.2	27	16.7	6	2	2.14	−21
	65–105	3.49	153.1	394	331.9	582	2	0.50	−344

†LOI: loss on ignition; WSP: water soluble phosphorus; TP: total phosphorus; M-P, M1-Al, M1-Fe: Mehlich 1-phosphorus, aluminum, and iron, respectively.
‡PSR: calculated from M1-P, Fe, and Al.
¶SPSC: soil P storage capacity calculated based on a threshold PSR of 0.1.
ND: below the detection limit of the instrument.

included dairies, improved and unimproved pastures, tree crops, citrus, forested, and other areas (Figure 5(a)). The SPSC values corresponding to these locations are shown in Figure 5(b). A general (visual) observation indicates that the SPSC under forested areas typically is positive while those under heavy P-impacted areas such as dairies and heavily fertilized citrus locations are negative. The SPSC would be an indicator of the P storage and loss at a given site even when previous use of the land is unknown. The study lays the basis for future research that may be conducted to evaluate P storage and losses from differing land uses to any designated depth across a watershed.

3.4. Application of SPSC to Wetland Soils. Wetlands are often considered to be a P sink. For most soil characterization for wetlands, soils are collected within a range of 10 to 50 cm depth depending on the objective of the investigation [33] which is often related to the rooting depth of the soil-plant system. To illustrate the importance of subsurface soil sampling, soils were collected from a wetland and an adjacent ditch (known to be heavily P-impacted) in the Lake Okeechobee Watershed, by depth until a Bh horizon was encountered. The upper boundary of the Bh horizon for the wetland soil profile occurred at 125 cm, and that for the ditch soil profile at 65 cm. At the Bh horizon, the Mehlich 1-Al was the highest for both of the soil profiles (Table 3, [34]). For the wetland soil SPSC was negative (P source) until the Bh horizon was reached where additional P storage was available. For the ditch sample, however, the Bh horizon was also negative indicating that the Bh horizon was also compromised and was a P source.

4. Future Research

(a) *Extrapolating the SPSC Concept to a Watershed Level.* The examples cited above show the potential of SPSC to be used on a site-specific basis. Further, indications are that the approach could be used to predict P storage and release across a watershed, irrespective of the land use. Since this tool has been extended to wetlands, ditches, and streams, SPSC will likely be useful for predicting P releases from soils within a watershed. With the advantage of SPSC being additive such that a single value can be obtained for a given soil profile to any desired depth, it should be possible to identify locations within a watershed that are subject to P loss via either surface or subsurface pathways, or through leaching. The approach would be useful to identify locations of legacy P accumulation and address the issue via appropriate best management practices (BMPs).

(b) *SPSC for Agronomic Purposes.* Current agronomic recommendations are based on STP values such as Mehlich 1 or Mehlich 3. For agronomic management of land application of manure, SPSC will be able to predict how much P can be safely applied to a soil before the soil becomes an environmental risk (i.e., until SPSC becomes negative). This is particularly critical when manure application is based on N requirements of a crop instead of P requirements. This calculated "lifespan" for P application to a site would be dependent on the retention characteristics of the soil and would therefore be site-specific. It is not possible to make similar predictions based on STP values.

(c) *SPSC for Predicting Isotherm "K" Values.* A recent review by Nair [18] indicated that isotherm K values become zero once the threshold PSR is reached; below the threshold PSR value, the K value is variable since K would be dependent on the amount of Fe + Al in the soil. Preliminary studies by Dari et al. [35] showed that positive SPSC (which, unlike the PSR, takes into account the additional P storage available based on the soil's Fe + Al content) is related to the Langmuir strength of P bonding, K_L; when SPSC is negative, K_L is zero. Once the relationship is verified, SPSC

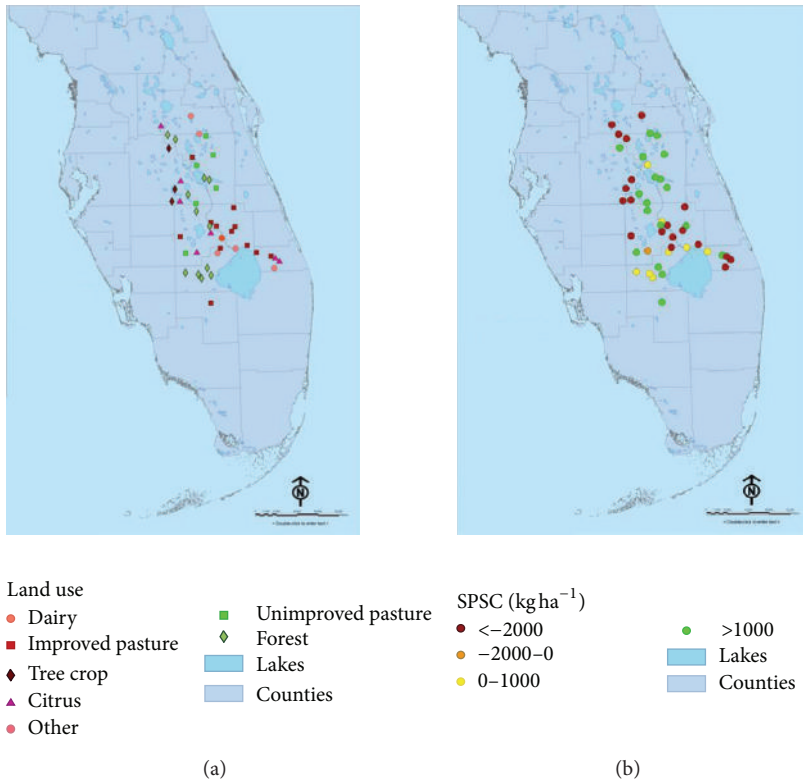


Figure 5: Land uses (a) and soil P storage capacity (SPSC; (b)) in kg ha^{-1} in the Lake Okeechobee Watershed of Florida, USA. Source: Showalter et al. [32].

obtained from soil test data would enable prediction of isotherm K values without the need for generating time-consuming isotherms.

(d) *SPSC for Urban Lands*. Another potential application of SPSC is its use as a tool to evaluate locations for stormwater retention ponds. The higher the SPSC at a given location, the greater the potential for the retention pond to filter P. Similarly SPSC would be of use in selecting fill material during construction.

(e) *Use of SPSC for Establishing Suitable Constructed Wetlands Locations*. The benefit of SPSC for evaluating the suitability of a site for construction of wetlands would be similar to that for constructing retention ponds. High positive SPSC would be a preferred location for constructed wetlands; negative SPSC suggests the soil is already a P source and therefore unsuitable for establishing constructed wetlands.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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