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A capacity factor as an alternative to soil test phosphorus in phosphorus risk assessment

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Abstract Soil test phosphorus (P) concentrations (STP) are often used as measures of environmental P risk. However, a low STP is not valid justification for further P application because P sorption capacity may be low and P added could be lost to surface waters. The degree of P saturation (DPS) normalises extractable P using extractable Al and Fe as a surrogate for P sorption capacity, but like STP, fails to convey a magnitude of capacity. We propose the use of a DPS-based prediction of the remaining soil P storage capacity (SPSC) that would capture risks arising from previous loading as well as inherently low P sorption capacity. The SPSC is a direct estimate of the amount of P a soil can sorb before exceeding a threshold soil equilibrium concentration. In this paper, we demonstrate the applicability of the SPSC for a variety of sandy soils impacted by dairy and poultry manure additions. The SPSC provides a means to assess the capacity of a soil to retain additional P and hence is a more useful indicator of P-related environmental risk than STP or DPS measures alone.

Keywords degree of P saturation; phosphorus saturation ratio; poultry and dairy manure; sandy soil profile

Abreviations DPS, degree of phosphorus saturation; SPSC, soil phosphorus sorption capacity; STP, soil test phosphorus; PSR, phosphorus saturation ratio

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INTRODUCTION

Standard soil test methods developed for agriculture have been used in recent years to assess environmental risks of phosphorus (P) loss from soils (Sharpley 1995; Hooda et al. 2000; Maguire & Sims 2002a). However, application of soil test P (STP) as an environmental indicator requires additional calibration beyond that conducted for fertility recommendations (Sharpley et al. 1999). Such calibration has led to the development of threshold STP concentrations and has been established for several regions. Sharpley & Tunney (2000) assembled examples of the use of such tests as guides for P management recommendations to protect water quality.

The concept of the degree of P saturation (DPS) for sandy soils was introduced in the Netherlands (van der Zee et al. 1987; Breeuwsma & Silva 1992), but has been extended to other parts of the world. The DPS normalises extractable P (oxalate, Mehlich 1 or Mehlich 3) to extractable Fe and Al, and has been related regionally to soil solution P concentration. This enables establishment of threshold values corresponding approximately to a set critical solution concentration of P (e.g., 0.10 mg litre^{-1}) (Breeuwsma & Silva 1992; Nair et al. 2004). The original method of calculation of the DPS specified oxalate-extractable P, Fe, and Al (Breeuwsma & Silva 1992; Koopmans et al. 2003).

The difficulty in using extraction methods not routinely used in soil testing laboratories led to modifications in DPS calculations to include STP values regularly performed in most laboratories (Kleinman & Sharpley 2002; Nair et al. 2004). Mehlich 1 extracts (Nair & Graetz 2002; Nair et al. 2004) and Mehlich 3 extracts (Kleinman & Sharpley 2002; Maguire & Sims 2002b; Sims et al. 2002; Nair et al. 2004) have been shown to be suitable to calculate DPS for sandy soils of south-eastern United States. McDowell & Condron (2004) derived relationships for subsurface flow and overland flow for a range of New Zealand soils using Olsen P and P saturation index (or P retention) data.

Heavy loading of P to sandy soils with very low P sorption capacities can quickly present environmental problems, despite initially low STP values. Environmental risk of P application relates to P sorption capacity up to some threshold where additional P could be detrimental. Several authors have reported "change points" in the relationship between soil extractable P and P concentrations leaving a farm via surface runoff or leaching (Hesketh & Brooks 2000; McDowell & Sharpley 2001; Maguire & Sims 2002a). Phosphorus additions that result in STP concentrations above a change point increase the risk to water quality.

The use of STP or DPS as environmental indictors of P loss from a farm has the shortcoming of failing to indicate the capacity of a soil to retain added P. Thus, soils with very low STP values may nevertheless have insufficient capacity to retain added P, and soils with higher STP values may have capacity to retain additional P. We propose the use of a DPS-based calculation of the remaining soil P storage capacity (SPSC) that would consider risks arising from previous loading as well as inherently low P sorption capacity. The SPSC provides a direct estimate of the amount of P a soil can sorb before exceeding a threshold soil equilibrium concentration. The purpose of this paper is to explain the basis of SPSC and to demonstrate its applicability for a variety of sandy soils impacted by dairy and poultry manure additions.

MATERIALS AND METHODS

Site locations

Soils for this study were located in two major catchments in Florida, United States: the Middle Suwannee River Catchment (Suwannee) and the Lake Okeechobee Catchment (Okeechobee). The Suwannee is home to 46 dairy and 142 poultry operations. Waste from these operations has the potential to pollute the Suwannee River via leaching in sandy soils and subsurface flow to springs along the river (Glasgow 1999). The dominant soils of the Suwannee are relatively well-drained Entisols (Quartzipsamments) and Ultisols (Paleudults) (Soil Survey Staff 1999). Soils of the Okeechobee in south-central Florida commonly are poorly to very poorly-drained Entisols (Psammaquents), Spodosols (Alaquods), and Alfisols (Endoaqualfs and Glossaqualfs). Most dairies in the Okeechobee are located on Spodosols. The land-use in the Okeechobee is mainly agriculture, with dairy farming as the most intensive land use (Boggess et al. 1995).

Soils from two dairy (Dairy 1 and Dairy 2) and two poultry (Poultry 1 and Poultry 2) operations with different P loadings within the Suwannee were selected for this study. Soils from Dairy 1 and Poultry 1 were minimally P-impacted (<30 mg Mehlich 1-P), whereas soils from Dairy 2 and Poultry 2 were heavily P-impacted (>150 mg Mehlich 1-P). Also studied were soils from three dairy pastures (Dairies 3, 4, and 5) within the Okeechobee Catchment of Florida, and non-manure-impacted or native areas within each catchment.

Soil sampling

There were four sampling locations at each of the selected sites. All soils (36 soil profiles) were sampled by horizon to a 2-m depth, using a 5-cm diameter auger. Typical horizons for the Suwannee include Ap, and E (no Bt within the surface 2-m depth) or Ap, E, and Bt up to a 2-m depth. Soils of the Okeechobee have an A horizon above an eluted E horizon, which is underlain by Bh (spodic) and Bw horizons (Soil Survey Staff 1999).

Soil analyses

Mehlich 1-extractable (0.0125 M H_2SO_4 + 0.05 M HCl) P (M1P), Fe (M1Fe), and Al (M1Al) were obtained using a 1:4 soil:Mehlich 1 solution ratio (Mehlich 1953). All metals and P in the Mehlich 1 solution were determined using inductively coupled argon plasma spectroscopy (Thermo Jarrel Ash ICAP 61E, Franklin, MA).

Calculations

The "P saturation ratio" (PSR) based on Mehlich 1 extractions for each soil sample was calculated as:

$$PSR = M1P/(M1Al + M1Fe)$$ (Nair et al. 2004).

All elements are expressed in moles. The PSR is equivalent to DPS, but without a corrective constant (α) associated with definition of DPS (Breeuwsma & Silva 1992). We use PSR instead of DPS in our calculations of SPSC for the purpose of simplicity.

The SPSC of a soil was based on a threshold PSR of 0.15:

$$SPSC = (0.15 - PSR) \times (M1Al + M1Fe)$$

where (M1Al + M1Fe) is proportional to the P sorption capacity of a given soil (van der Zee et al. 1987). The value of 0.15 is used in the SPSC calculation as the best approximation we have to date of the PSR value (Nair et al. 2004) corresponding to the critical P solution concentration of 0.10 mg litre^{-1} P as proposed by Breeuwsma & Silva (1992).

The SPSC for a given soil horizon expressed as kg of P m^{-3} was calculated from an assumed

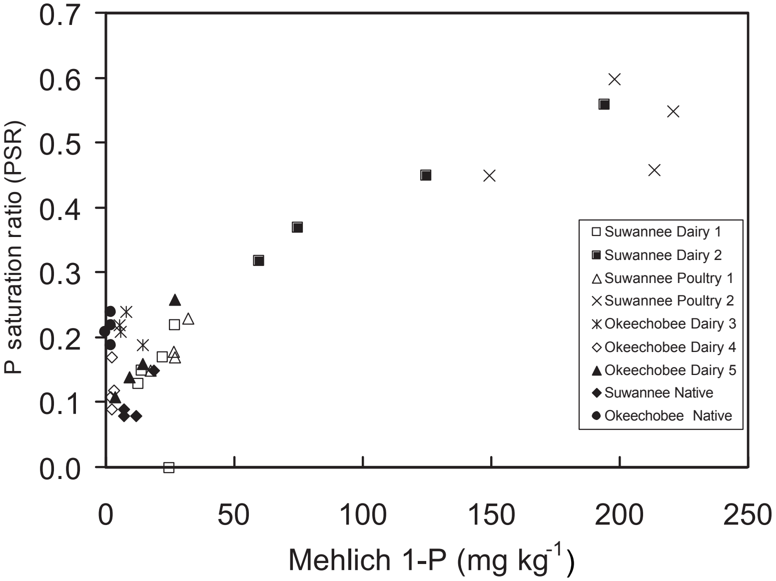

Fig. 1 Phosphorus saturation ratio (PSR) as a function of Mehlich 1-P for surface soils of the Suwannee and Okeechobee Catchments.

bulk density of 1.5 kg m^{-3} and the thickness of the horizon. The SPSC can also be expressed as mg P kg^{-1} or kg P ha^{-1} (for a specified depth), and can be used to calculate the lifespan of a soil with respect to further safe P additions.

RESULTS AND DISCUSSION

Surface soils of the Okeechobee with low Mehlich 1-P concentrations (<15 mg P kg^{-1}; Kidder et al. 2002) can have corresponding PSR above the threshold value of 0.15 (Fig. 1). This indicates that the soils have little P-sorbing capacity, and further addition of P to such soils could result in an environmental risk, despite low Mehlich 1-P values. Mehlich 1-P is used in the Florida P-Index (2004), a P loss risk assessment tool developed for Florida soils. Phosphorus indices have been developed for almost all states in the United States for P loss risk assessment and several indices use STP as part of the evaluation. The approach discussed here may be applicable to sandy soils in several parts of the world, including the New Zealand grassland soils (McDowell & Condron 2004), the coastal plain soils of the southeastern United States (Nair & Graetz 2002; Sims et al. 2002), and the sandy soils of the Netherlands and the Po valley of Italy (Breeuwsma & Silva 1992).

A low PSR soil may be unable to retain additional P if the soil has a low adsorption capacity. For example, the native soils from the Suwannee have PSR below the proposed limit of 0.15, suggesting that they have some capacity to safely store additional P. However, the magnitude of that capacity is not defined by the PSR. The SPSC, on the other hand, enables prediction of the amount of additional P that can be accommodated by a given soil horizon before the added P becomes an environmental concern. Some native soils of the Okeechobee have low PSR values, but limited SPSC (Fig. 2), whereas some native surface soils of the Suwannee, with low PSR values, have higher SPSC values (Fig. 2).

A soil profile in a minimally-impacted dairy spray field in the Suwannee (Dairy 1) showed a large amount of remaining SPSC (Fig. 3). On the other hand, a heavily manure-impacted spray field in the same basin (Dairy 2) showed no remaining SPSC to a 2-m depth (Fig. 3). This dairy has negative SPSC in the surface horizons as well as the Bt horizon, indicating that the soil profile (to a 2-m depth) would be a P source rather than a P sink. Heavy manure application at the Poultry 2 site in the Suwannee resulted in the A and E horizon being P sources, while the subjacent Bt and Btg horizons serve as P sinks (Fig. 4).

For all soils, the risk of P movement off site is strongly tied to hydrology. In effect, the risk would be relatively low notwithstanding high STP values or negative SPSC in the near-surface horizons if water moved vertically through the Bt. On the other hand, risk would be greater in the case of surface runoff or lateral subsurface flow through fissures that permit

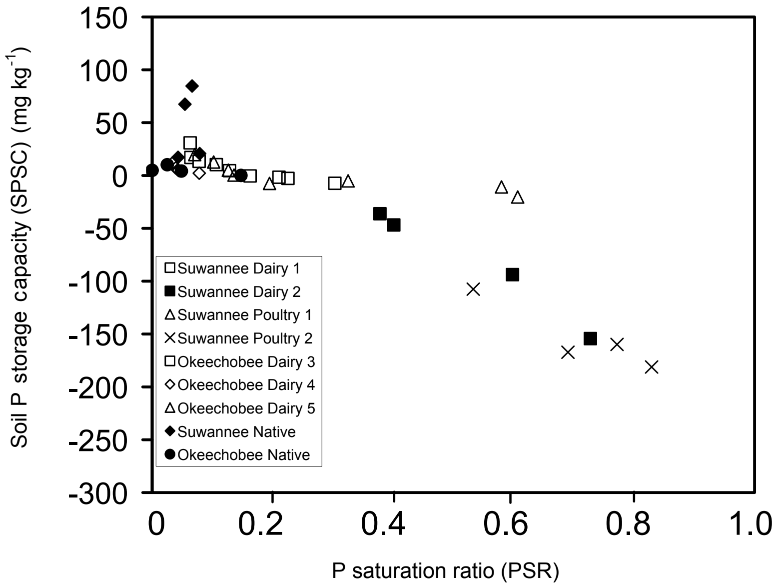

Fig. 2 Soil P storage capacity (SPSC) as a function of the phosphorus saturation ratio (PSR) for surface soils of the Suwannee and Okeechobee Catchments.

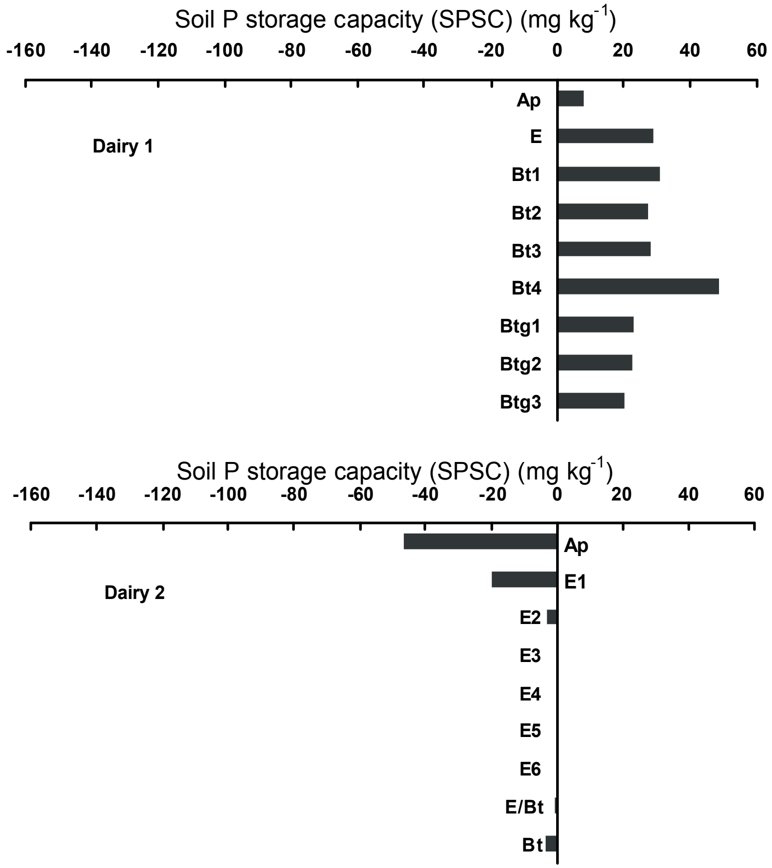

Fig. 3 Soil phosphorus storage capacity (SPSC) calculated using Mehlich 1-P, Fe, and Al concentrations for a minimally P-impacted dairy soil (Dairy 1) and a heavily P-impacted dairy soil (Dairy 2) in the Suwannee Catchment.

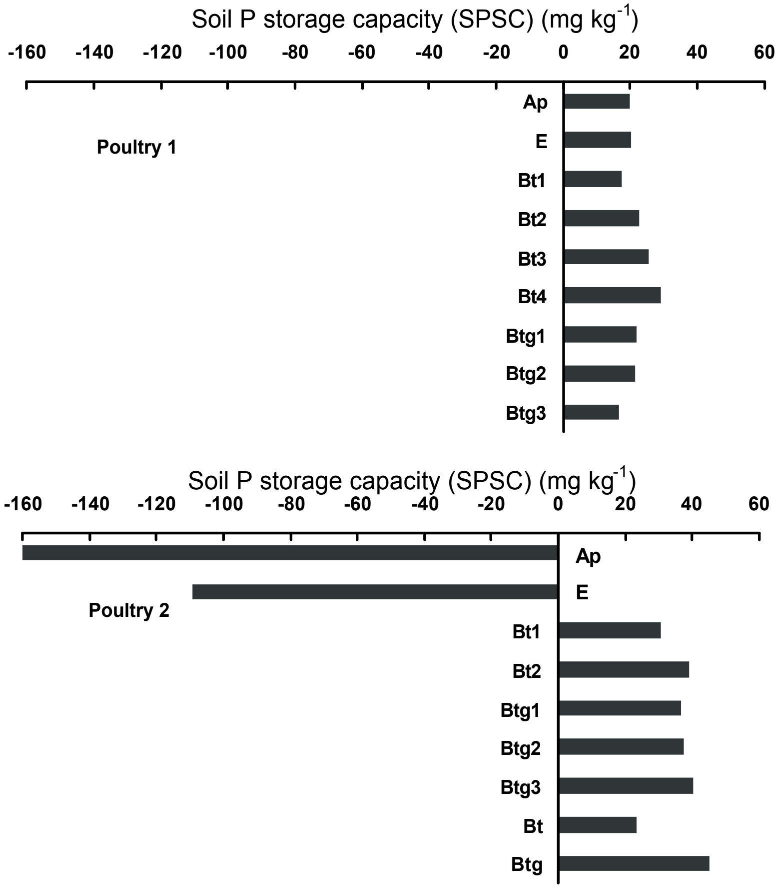

Fig. 4 Soil phosphorus storage capacity (SPSC) calculated using Mehlich 1-P, Fe, and Al concentrations for a minimally P-impacted poultry soil (Poultry 1) and a heavily P-impacted poultry soil (Poultry 2) in the Suwannee Catchment.

short-circuiting of the Bt horizon. The less manure-impacted soils of Poultry 1 had significant remaining P storage capacity throughout the soil profile (Fig. 4).

The soil profile from Dairy 3 within the Okeechobee is representative of a dairy pasture that has exhausted its SPSC in the surface A and E horizons, but has ample P storage capacity in the spodic (Bh) and the Bw horizon underlying it (Fig. 5). Other researchers (Mansell et al. 1991; Nair et al. 1998) have noted the high retention capacity of the Bh horizon in Spodosols compared with the surface A and E horizons. Yuan & Lucas (1982) found the A horizon of Spodosols showed negative sorption values. The results for the other two dairies (Dairies 4 and 5) showed similar SPSC trends (data not shown) in the soil profile as Dairy 3. Phosphorus reaching the spodic horizon would be retained by the soil, but high water-table conditions in this catchment would probably promote P loss via surface and subsurface drainage. The P could bypass, or never even reach, the spodic horizon (Campbell et al. 1995).

It is possible to use the SPSC concept on any sandy soil for which the P saturation ratio has been determined (irrespective of the procedure used in the PSR calculation). PSR values will have to be determined based on the soil test used at a given place. The (Fe+Al) multiplication factor is not an exclusive surrogate for P sorption, though a number of studies (Breeuwsma & Silva 1992; Nair et al. 1998; Schoumans & Groenendijk 2000) have shown it to be a very good predictor for sandy soils. The (Fe+Al) factor could be replaced by other P sorption parameters if the latter were preferable measures of sorption capacity for specific regions. The calculated SPSC for a given extractant or P sorption assessment might require some calibration for that combination of terms.

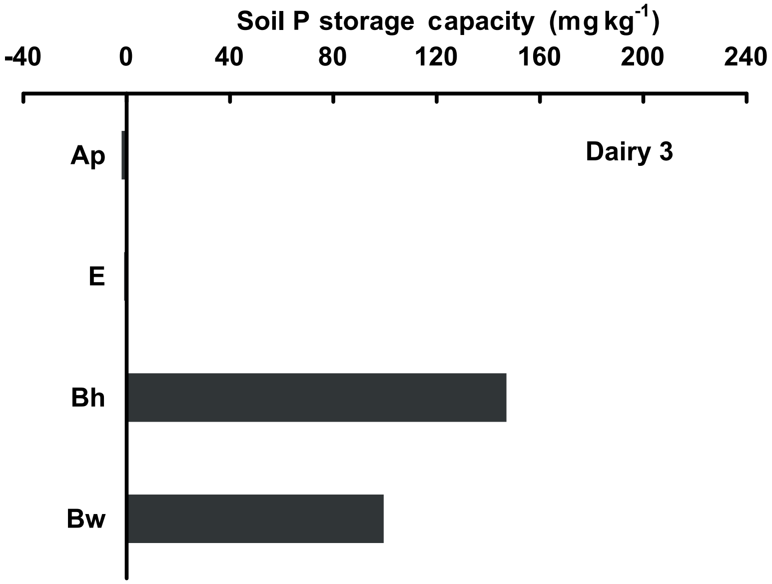

Fig. 5 Soil phosphorus storage capacity (SPSC) calculated using Mehlich 1-P, Fe, and Al concentrations for a P-impacted dairy soil (Dairy 3) in the Okeechobee Catchment. Note the difference in the *x*-axis scale for this dairy and the dairies in the Suwannee Catchment (Fig. 3, 4).

CONCLUSIONS

Some sandy soils (e.g., Spodosols of the Okeechobee), with low Mehlich 1 STP and PSR values can quickly reach high-risk concentrations with P loading due to low sorption capacities. Hence, a low STP or PSR value is not a valid reason to excessively supply P in the nutrient management scheme. The SPSC provides a solution to two limitations of STP and DPS in assessing P loss risk: (i) it captures risk arising from low P sorption capacity, and (ii) it has potential to be used as a predictor of the lifespan of a prospective manure application site under a given loading regime.

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