

# The Persistent Environmental Relevance of Soil Phosphorus Sorption Saturation

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**Abstract** Controlling phosphorus (P) loss from agricultural soils remains a priority pollution concern in much of the world. Dissolved forms of P loss are among the most difficult to manage. The concept of soil P sorption saturation, the extent to which a soil's binding sites for P are occupied, emerged from the Netherlands in the 1990s and has broad appeal as both environmental indicator and management paradigm. For hydrologically active and connected soils, P sorption saturation is responsible for the stubborn problem of legacy P, resulting in long-term release of dissolved forms of P from soils. Short- and long-term mitigation options for elevated soil P sorption saturation do exist, all with trade-offs that require adoption of new mitigation and prevention strategies. Ultimately, better incorporation of soil P sorption saturation into both crop fertility and environmental management programs is needed to promote the sustainable management of P in agricultural production systems.

**Keywords** Phosphorus · Soil · Eutrophication · Phosphorus sorption saturation

## Introduction

Persistent concerns over the eutrophication of lakes, rivers, and coastal waters have led to the recognition that dissolved phosphorus (P) loss in runoff from agricultural landscapes is

one of the most difficult forms of pollution to control [62]. Diffuse sources of agricultural P are implicated in marquee cases of eutrophication, from Lake Tai in China, to Lake Erie in the North America, to the Baltic Sea in northern Europe, to the Rotorua Lakes of New Zealand. In the USA alone, freshwater eutrophication is estimated to cost \$2.2 billion annually in lost services [8], while comparable costs for England and Wales are as high as \$160 million per annum [51]. Although agricultural sources of P are diverse, none are as pervasive and persistent as P in soils. With the caveat that active hydrology is necessary to mobilize soil P and convert it from fertilizer resource to off-site water quality concern [50], the accumulation of P in soils, intended or unintended, results in chronic releases of P to runoff, dubbed “legacy P” for its origin from historical fertilization activities [24]. Identifying, targeting, and managing legacy P in agricultural soils is therefore fundamental to the success of watershed phosphorus programs [62].

At one level, the accumulation of P in soils represents the intended outcome of agricultural development, simultaneously highlighting the success and inefficiency of strategies that fertilize soils in order to supply nutrients to crops. It is essential to keep in mind that soil fertility principles are at the foundation of successful agricultural development around the world [52, 75], with no example more dramatic than the reclamation of Brazil's Cerrado region into the cereal farming and economic engine that it is today [14]. Central to soil fertility management are the concepts of nutrient “Quantity” (i.e., P that is bound in solid phase and only partially available to the soil solution through the pseudo-equilibrium processes of “desorption”) and nutrient “Intensity” (i.e., inorganic P in the soil solution that is readily absorbed by crop roots).

To increase P Intensity to concentrations needed to support modern crop yields, changes are required in the native chemistry of most soils [69]: if needed, liming acidic soils to near

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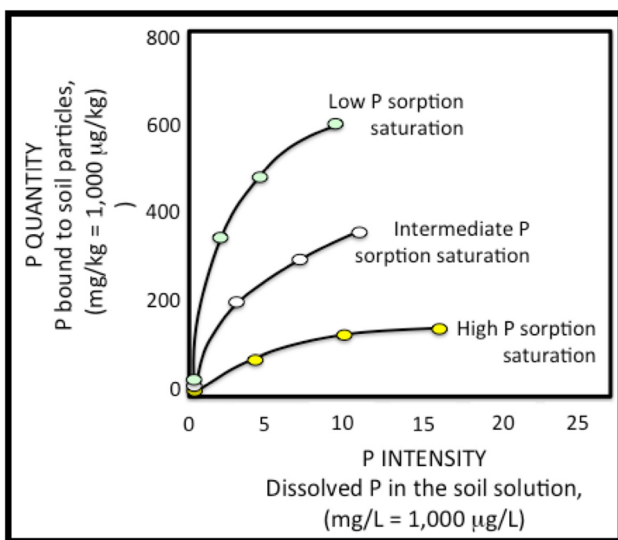
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neutral pH, and adding large amounts of P to soils to overcome their tendency to bind dissolved forms of P (termed “P sorption” to include the combined processes of “adsorption” of P to the surface of mineral colloids and “precipitation” of P with cations such as Fe, Al, and Ca). Because diffusion of P in soils is very limited, soil fertility strategies seek to build P throughout the rooting zone. Thus, soils are managed as a bank account for fertilizer P, represented by P Quantity, which supplies regular withdrawals of P from the Intensity pool by high-yielding crops.

This primer on soil fertility management highlights the inequitable distribution of P in well-managed soils, especially the large reserves of P in the soil solid phase that maintain dissolved P concentration solution. Because the P Quantity component of fertile soils stores several orders of magnitude more P than the P Intensity component (Fig. 1), concentrations of P in solid phase are generally hundreds of milligrams per kilogram in order to sustain P Intensity values of a few milligrams per liter (or thousands of  $\mu\text{g/L}$ ). Furthermore, release of dissolved P from soils to runoff water from well-fertilized soils can sustain concentrations of thousands of micrograms per liter without any significant depletion of P Quantity [71]. In aquatic systems, concentrations of tens of micrograms per liter of inorganic P are all that is required to shift trophic status from pristine, oligotrophic conditions to disturbed, eutrophic conditions [6]. Therefore, traditional soil fertility management may be seen as a blunt instrument when applied to the environmental concern of dissolved P loss to aquatic systems.



**Fig. 1** Phosphorus sorption isotherms from three soils of similar classification but with varying levels of P sorption saturation. Differences in P sorption saturation reflect historical applications of P. Isotherms are obtained by shaking samples of an individual soil with varying concentrations of phosphate in solution for a given period of time, then determining the amount sorbed and relating that to the remaining concentration in solution. Adapted with permission from Kleinman et al. [21]

The principals of Quantity and Intensity from soil fertility management underscore the environmental concept of “soil P sorption saturation,” also called “soil P saturation,” “degree of P saturation,” “soil P saturation ratio,” or simply “P saturation.” Soil P sorption saturation sprang out of studies in Europe, particularly the Netherlands, in the 1980s and 1990s to explain dissolved P leaching to shallow ground waters [3, 28, 55, 74]. Previously, there was limited recognition that P could be transported through soils in dissolved form due to the sorption capacity of soils, which, under equilibrium conditions, would result in P removal from solution [64]. Breeuwsma and Silva [3] posited that P availability to leachate waters increased with the accumulation of P in the solid phase, as sorbed P essentially saturated reactive surfaces in soils and permitted more dissolved P to remain in solution. Phosphorus sorption saturation was defined as the quantity of P in soil relative to the soil’s capacity to bind, or “sorb” that P:

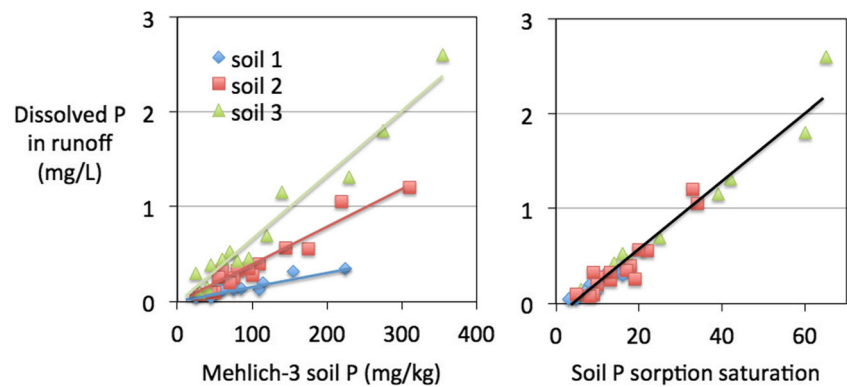
$$\text{P sorption saturation} = \text{Sorbed P} / \text{P sorption capacity} \quad (1)$$

### Soil P Sorption Saturation as an Environmental Indicator

Today, soil P sorption saturation is well established as a quantitative indicator of soil P release to both surface and subsurface runoff waters: as soil P sorption saturation increases, dissolved P concentrations in runoff waters increase [3, 16]. Among the most compelling findings supporting the use of soil P sorption saturation as a universal indicator of dissolved P release from soils are those reported by Sharpley [59] who observed a single quantitative relationship between dissolved P concentrations in runoff and soil P sorption saturation across diverse soils (other soil tests produced multiple quantitative relationships across the same soils; Fig. 2). Equally compelling has been the frequent conclusion that soil P sorption saturation improves prediction of dissolved P concentrations in soil leachate over other soil P tests [4, 26, 31].

Part of the explanatory power of soil P saturation comes from the reasonable concept that soils have a finite capacity to sorb P, and that capacity (the denominator of the saturation equation) is overwhelmed as sorbed P accumulates (the numerator). The presence of a P sorption ceiling, of course, is not entirely accurate as soils never become fully P saturated (i.e., completely incapable of sorbing further additions of dissolved P, as illustrated by the lack of a sorption plateau in Fig. 1). For instance, concerns of over-interpreting P sorption maxima extend back to early literature on the Langmuir sorption isotherm model [46], borne of observations that new reactive surfaces will form over time and that “slow” P sorption occurs as P is increasingly occluded within the physical matrix of soil aggregates or precipitated gradually by certain minerals [12,

**Fig. 2** The relationship of dissolved P concentration in runoff with Mehlich-3 soil P and soil P sorption saturation. Adapted from the rainfall simulation experiments of Sharpley [59]



54, 68, 73]. Even so, a finite P sorption capacity is a useful concept that describes a diminished capacity to both sorb additional P and buffer P in the soil solution [21, 42].

Soil P sorption saturation has been used to identify environmental limits, a perennial point of contention in nutrient management and environmental arenas alike. In the Netherlands, a soil P sorption saturation limit of 25% has been defined for water quality protection, where it is codified in the national soil law [29, 45]. This threshold stemmed from laboratory and soil column leaching studies (e.g., [56, 74]). Elsewhere, arguments for and against the use of agronomic soil test thresholds as environmental P thresholds have raged, particularly in the USA, where regulatory and privacy concerns have helped to color and politicize scientific debate (e.g., [17]). As a non-agronomic soil test, soil P sorption saturation is frequently proposed as an alternative, environmental soil test to which environmental thresholds can be defined [63]. Indeed, the utility of soil P sorption saturation in defining a remaining P sorption capacity in soils is that it can be used to strategically define and assess trajectories for P accumulation (e.g., [42]).

### Measuring Soil P Sorption Saturation

Despite widespread reports that P sorption saturation can improve the prediction of dissolved P in runoff waters over standard soil tests, there are few areas, outside of the Netherlands, where P sorption saturation is regularly applied as a soil test other than for academic research. This is largely because the original soil testing methods used to determine P sorption saturation were different than those used for making agronomic recommendations. It is also noteworthy that many of the studies showing improvements in predicting dissolved P loss from soils using soil P sorption saturation were highly controlled: often involving controlled irrigation events (rather than natural rainfall) and sometimes employing homogenized soils (rather than structurally intact soils). Other studies with lesser control on edaphic and environmental variability have found other soil P tests to perform adequately across broad

swaths of agricultural soils (e.g., [71]). Because most soil P tests correlate to each other to some degree [22, 30], including soil P sorption saturation [47, 56], and because agronomic soil P tests are already widely used in making soil fertility recommendations, there are practical considerations to be weighed when arguing for any particular indicator of dissolved P loss potential, including soil P sorption saturation.

### Acidic Soils

Due to the diversity of soils and inherent P reaction chemistries they support, no universal soil test exists to quantify P sorption saturation. For acidic soils, the acid ammonium oxalate test has been the most widely used method of quantifying the numerator (P sorbed) and denominator (P sorption capacity) of the P sorption saturation equation (Eq. 1); notably, the Langmuir maximum ( $S_{max}$ ), derived from sorption isotherms (depicted in Fig. 1), has consistently served as the reference point for those studies seeking to validate estimates of the P sorption capacity. The acid ammonium oxalate test has long been used in soil classification to quantify the presence of sesquioxides: amorphous oxides and hydroxyl-oxides of iron (Fe), aluminum (Al), and other so-called acidic cations (e.g., Mn). In acidic soils, these sesquioxides, with their high surface area and high reactivity with phosphate in solution, are a dominant contributor to P sorption capacity [13]. As a result, the molar concentrations of Fe and Al extracted with acid ammonium oxalate ( $Fe_{ox}$  and  $Al_{ox}$ ) have been used to quantify the P sorption capacity:

$$P \text{ sorption capacity} = a(Fe_{ox} + Al_{ox}). \quad (2)$$

Simultaneously, the molar concentration of P extracted by acid ammonium oxalate ( $P_{ox}$ ) can be used to represent the numerator (P sorbed) of the soil P sorption saturation equation (Eq. 1). With the advent of multi-element spectrometry, such as inductively coupled plasma–optical emission spectrometry (ICP-OES), all components of the soil P sorption saturation equation can be readily obtained from a single acid ammonium oxalate extract, a key, practical benefit to this approach.

While acid ammonium oxalate is a well-established extract of sesquioxides, the association is functional, at best, and is not isolated to only those sesquioxide surfaces with a potential to react with phosphate. Consequently, the soil P sorption capacity component is sometimes modified by the parameter  $\alpha$  to account for the fraction of  $\text{Fe}_{\text{ox}}$  and  $\text{Al}_{\text{ox}}$  that actually reacts with P (Eq. 2). As established in the Netherlands,  $\alpha$  is determined by the slope of the equation relating the Langmuir maximum from P sorption isotherms to the molar concentration of  $\text{F}_{\text{ox}}$  and  $\text{Al}_{\text{ox}}$  in a soil sample [53]. An  $\alpha$  of 0.5 is regularly observed for Dutch coastal plain soils. Due to the batch sorption studies needed to produce the isotherms, the determination of  $\alpha$  is a laborious, time-consuming step that is seldom performed. Not surprisingly, the literature is replete with studies from widely varying physiographic contexts that assume  $\alpha = 0.5$  but do not test that assumption. The use of an assumed  $\alpha$  is largely justified on the basis of enabling comparison with the Dutch regulatory threshold for soil P sorption saturation (e.g., [42]). Examples of studies outside of the Netherlands that measured  $\alpha$  include Pautler and Sims [47], who identified an  $\alpha$  of 0.68 for Delaware soils, as well as Nair and Graetz [39], who determined an  $\alpha$  of 0.55 for Florida soils. For studies that do not directly assess  $\alpha$ , Hooda et al. [16] correctly point out that assuming an  $\alpha$  of 0.5 is arbitrary and potentially misleading given the reported variability in  $\alpha$ . For soil P sorption saturation to become a routine soil test in other countries, soil testing programs would likely need to assess  $\alpha$  across the range of soil conditions for which they provide recommendations.

#### Alternatives to Acid Ammonium Oxalate

Soil testing has produced a myriad of extraction protocols, complicating efforts to consistently and systematically establish recommendations over large geographic areas. Acid ammonium oxalate is a very specialized test that is not offered by most commercial testing laboratories. To expand soil P sorption saturation into a routine soil test, a variety of studies have

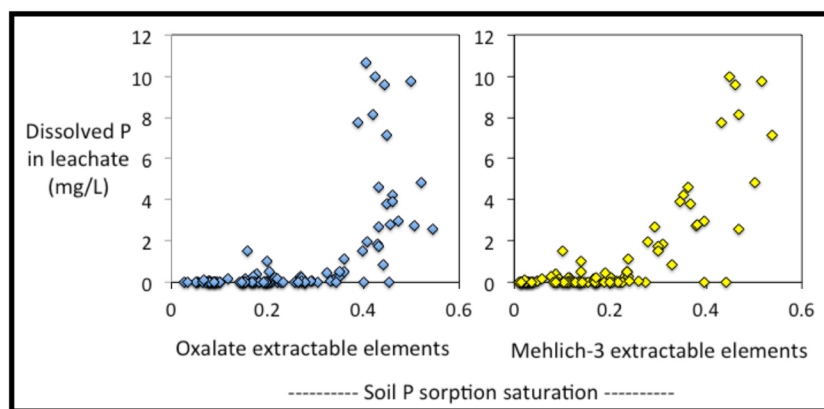
sought to estimate it using readily available agronomic soil tests. Pautler and Sims [47] found that soil P sorption saturation could be estimated using the Mehlich-1 soil test along with a single point sorption index, which is correlated with the Langmuir sorption maximum. Following their finding, others [20, 31, 48] demonstrated that P sorption saturation could be reliably estimated solely using Mehlich-3-extractable elements by substituting some combination of P, Fe, and Al from the Mehlich-3 soil test for acid ammonium oxalate elements. Maguire and Sims [31] also found soil P sorption saturation estimated with Mehlich-3-extractable elements to be an effective indicator of dissolved P concentrations in soil leachate (Fig. 3). If soil P sorption saturation is to be widely used as an environmental soil test, it will likely be through this type of adaptation of an agronomic soil test.

#### Alkaline Soils

To date, no single approach is recognized for estimating P sorption saturation in alkaline soils. Measuring soil P sorption saturation in alkaline, particularly calcareous, soils is difficult, if not problematic. The acid ammonium oxalate extract that is so well accepted for acidic soils cannot be used in alkaline soils as Ca, the major cation responsible for P sorption at higher soil pH levels, forms a precipitate that is not measured. As a result, other methods have been used to estimate P sorption saturation in alkaline soils, most involving batch sorption studies to estimate P sorption capacity (e.g., [20]).

Kleinman and Sharpley [20] observed strong relationships between soil P sorption saturation estimated with Mehlich-3-extractable P (the sorbed P variable) and Ca (the P sorption capacity variable) with soil P sorption saturation calculated from bicarbonate extractable P (sorbed P) and the sum of bicarbonate P and the Langmuir sorption maximum (P sorption capacity). When adjusting the estimate of P sorption capacity using a soil's clay content, that relationship improved. They concluded that for the alkaline soils in their study (pH 7.3–8.3), the Mehlich-3 extract could serve as one means

**Fig. 3** The relationship of dissolved P in leachate with soil sorption saturation as estimated using acid ammonium oxalate and Mehlich-3-extractable P, Fe, and Al. The soils evaluated in this study were all acidic. Adapted with permission from Maguire and Sims [31]



of estimating P sorption capacity. This approach requires further investigation before being widely recommended since (a) Fe can play a significant role in P sorption in alkaline soils [49] and (b) Mehlich-3, an acidic extract (pH = 2.5), is not generally used on calcareous soils due to its weak buffering capacity and its inclusion of  $\text{NH}_4\text{F}$  which precipitates  $\text{CaF}_2$  [36].

### Soil Sampling Considerations

Soil P sorption saturation is decidedly an environmental indicator. While measurements of soil P sorption saturation from samples obtained via normal agronomic methods are of value, the utility of soil P sorption saturation measurements can be increased by prudent sampling of soil zones most likely to serve as a source of P to runoff waters [2]. For surface runoff, it has been estimated that the primary source of P from soils is in the upper 2–4 cm [58]. As a result, many studies of P loss to surface runoff rely upon shallow soil samples. Increasingly, there is concern about P accumulation on the soil surface, particularly on soils with perennial covers or on not-tilled soils. Following only a few years of fertilization, concentrations of P at the soil surface can be more than 50% greater than those observed in standard 20-cm-deep samples [1].

Studies of P leaching to shallow groundwater have also linked concentrations of P at the soil surface with P in leachate (e.g., [34]). It is generally thought that P leaching to groundwater occurs via quick flow that mobilizes peak concentrations of P at the soil surface and bypasses the sorption capacity of the soil matrix via macropores [34]. Evidence for this process includes diminished P sorption saturation of the walls of soil macropores relative to the surrounding matrix [23]. As a result, shallow soil samples can also be used to assess P leaching for most soils. However, for soils with severe P sorption saturation, other sampling depths may offer insight into the extent of the potential pollution source. For instance, as soil P sorption saturation increases near the surface and more P is maintained in the soil solution, P diffusion and advection into the deeper matrix increase, resulting in greater P sorption saturation of those depths.

Kleinman et al. [26] evaluated P leaching from an array of acidic soils, many with high soil P sorption saturation due to historical application of large quantities of poultry manure as fertilizer. As with previous studies, they found soil P sorption saturation to better predict dissolved P in leachate than other tests, including Mehlich-3 P. When they examined relationships between dissolved P in leachate and different soil tests, they found strong statistical relationships at shallow (0–5 cm) and deep (45–50 cm) depths, although the spread of that relationship was wider, and therefore easier to discern, in shallow samples than in deep samples. Some precedent exists for using deep soil samples to assess P leaching potential, particularly in the nutrient management guidelines of the US state of North

Carolina [43]. Notably, in the study of Kleinman et al. [26], apparent P sorption saturation thresholds for dissolved P concentrations in leachate were higher for shallow samples (P sorption saturation <0.2) than for deep samples (P sorption saturation ~ 0.6).

### Management of Soil P Sorption Saturation

Reduced to a management algorithm, soil P sorption saturation can be parsed into practices and strategies geared toward managing the quantity of sorbed P in soil and the P sorption capacity of soils. This division is admittedly artificial, as management options for one can also apply to the other, but it does elucidate the need to both address P that is being added to soil as well as the conditions of that soil before P additions are made.

#### Managing the Numerator (Sorbed P)

The most obvious approach to managing soil P sorption saturation is to focus on the mass balance of P, presumably the numerator of the P sorption saturation equation (Eq. 1). For soils with lower soil P sorption saturation, opportunities exist to improve agronomic soil testing as well as to establish environmental thresholds that restrict further additions of P to soils. For soils with a high soil P sorption saturation, the natural management recommendation is to cease further P applications and draw down the quantity of sorbed P in the soil and hence the P sorption saturation.

Preventing the accumulation of P in soils above levels that threaten water quality is clearly preferable to implementing remediation programs that treat P as a pollutant, rather than a resource. Proscriptive programs must consider the soil fertility needs of a crop as well as the non-point source pollution concern (see below for discussion of environmental thresholds). There is precedent for considering soil P sorption saturation in making agronomic recommendations. For instance, in Australia, extractable Al has been used to adjust P fertilizer recommendations to account for variability in the inherent P buffering of different soils [37]. This is not needed, however, to prevent excessive soil P sorption saturation on farms where prudent nutrient management decisions are grounded in recommendations from soil fertility testing.

There is undoubtedly a need to revisit the existing P fertility recommendations, most of which were historically developed when concerns over dissolved P loss to runoff were not recognized. Globally and locally, there is a critical need for consistency across the multitude of fertilizer recommendation sources, a task that has been admirably confronted by the Better Fertilizer Decisions Program of Australia [66]. At an even more profound level, there is need to systematically confront biases and error underscoring historical decisions made in soil fertility testing.

For instance, fertilizer recommendation philosophies have differed in whether they emphasize the correction of nutrient deficiency (also called the “sufficiency” approach) or the maintaining nutrient supply above levels where deficiency may arise as a concern (the “maintenance” approach). Not surprisingly, researchers have questioned whether soil P recommendations are unnecessarily high [65]. Further, most fertilizer recommendations owe their foundation to research performed over the past six decades. During that time, major changes have occurred in the crop varieties, fertilizer formulations, fertilizer application methods, and other factors affecting soil P availability to crops. There is also a more sophisticated understanding of interactions between P and other controls on crop growth that has been absorbed by cropping models. Therefore, opportunity exists to tackle conflicts between agronomic recommendations for P fertilization and environmental concerns related to soil P sorption saturation (e.g., [65]).

Long-term studies of soil P “draw-down” (also termed “phytomining” by the Europeans) are uncomplicated to perform but are scarce in number, likely due to the commitment required to sustain them [9, 11, 19, 24, 33, 35, 67, 72]. In general, the higher the antecedent content of sorbed P, the more biomass harvest is required to draw down soil P to reasonable levels, and, therefore, the longer the waiting period to lower soil P to reasonable levels. As a result, forage cropping systems are generally thought to be better for P draw-down in soil than cereal grains [11, 27]. In addition, perennial forages provide greater protection against erosion, and therefore better mitigation of particulate P loss, than do annual crops.

In employing mass balance approaches to soil P management, it is essential to keep in mind the earlier discussion regarding the laboratory measurement of soil P sorption saturation. This measurement is constrained by the properties and efficiencies of the extracts (e.g., acid ammonium oxalate). As extracts do not perfectly mimic plant uptake, seldom is there a 1:1 correlation between an extract and field calculations of P addition and removal. For instance, the removal of 30 kg/ha P in crop harvest will likely be manifest in different measured changes in P sorption saturation in soils with different P buffering capacities. In addition, changes in climate, cropping systems, and agronomic management can result in substantial variability in soil P pools and soil test extraction efficiencies [24].

### Managing the Denominator (P Sorption Capacity)

The addition of P sorption capacity to soils to lower P sorption saturation and dissolved P concentrations in runoff has attracted research worldwide. As large amounts of an amendment are generally needed to adequately buffer a soil, most research has gravitated toward the use of by-product materials, with agriculture serving as a potential beneficiary of another industry’s waste. As a rule of thumb, materials rich in Al and Fe have been evaluated for acidic soils, whereas Ca-based

amendments have been tested on alkaline soils. Examples of successfully trialed amendments include alum, gypsum, water treatment residuals, and acid mine treatment residuals, although many more materials have been tested and shown to lower P solubility [5, 38, 44].

The direct application of amendments to soils to improve P sorption saturation generally requires strong regulatory drivers given associated costs. Even when waste materials are free, transportation costs can be prohibitive for farmers if only water quality objectives are sought. In some cases, amendments may confer other benefits that serve as incentives for their use: supplying macro-nutrients (e.g.,  $\text{CaSO}_4$ ), promoting good soil structure (e.g., flocculants), and mitigating adverse soil conditions such as salinization [70].

A more indirect approach may also be taken to increasing the P sorption capacity of soils by amending manures with P sorbing salts. In the USA, alum ( $\text{Al}_2[\text{SO}_4]_3$ ) may be added to the dry manure (litter) of broiler chickens to control ammonia emissions in barns (alum is a weak acid that prevents ammonia volatilization). Huang et al. [18] demonstrated that long-term (20 years) additions of alum-amended chicken litter to acidic pasture soils increased the P sorption capacity at the soil surface, reducing dissolved P losses in runoff by over 40% compared with un-amended chicken litter. Furthermore, they observed lesser diffusion and advection of P into the subsoil of soils receiving alum-amended litter, likely due to greater sorption of an organic form of P (phytate) that is a major fraction of P in chicken manure. Therefore, even though more P was retained at the surface of the pasture soils with alum-amended litter, the greater P sorption capacity of the soil stabilized mineral and organic forms of P so that they were less soluble in runoff waters [18].

The management of soil pH plays a key role in soil P solubility. For instance, in the draw-down study reported by Kleinman [25], liming of an acidic soil resulted in a dramatic increase in the amount of P that was extractable by a soil test (Mehlich-3), such that concentrations after 10 years were the same as at the start of the study. Certain crops, such as legumes, require higher soil pH than do other crops [10]. Soil P solubility tends to be greatest between pH 6.5 and 7.0, the preferred range for most legumes. Above pH 5.4, Al solubility declines while Ca controls on P solubility do not peak until more alkaline conditions favoring the stability of Ca-P precipitates [57]. Therefore, in acidic soils with high P sorption saturation, mitigation strategies should consider the pH requirements of crop rotations and promote parsimonious liming strategies that seek, if necessary, to address aluminum toxicity without elevating soil pH to levels where P solubility is maximized (i.e.,  $\text{pH} \geq 6.5$ ).

### A (Controversial) Role for Tillage

Vertical stratification of P and increased P sorption saturation of the soil surface is a ubiquitous management concern,

ranging from obvious cases where historical over-application of P has built up P to levels far beyond agronomic justification, to the unintended consequence of conservation programs that prevent fertilizer and manure from being routinely incorporated below the soil surface. Tillage, a practice anathema to the philosophical leanings of many in the soil conservation community, can be an effective tool in mixing soil from the surface with subsoil. Given the non-linear nature of P sorption, even small amounts of soil with low P sorption saturation can dramatically reduce the concentration of P in the soil solution (e.g., [32]). However, the erosion consequences of the tillage must be measured against the potential benefits of lowering soil P sorption saturation at the surface.

In a highly controlled study using rainfall simulators and packed soil boxes, Sharpley [60] explored the consequences of mixing soils with severe vertical stratification of P. Mixing of a surface soil with antecedent soil P sorption saturation of 0.65 with subsoil resulted in a final P sorption saturation of 0.07. While this mixing temporarily elevated total P concentrations in runoff in the first events after tillage compared with the untilled control, there were long-term reductions in total P concentrations with tillage. With tillage, the collateral consequences on erosion were short-lived, whereas the benefits of reduced P sorption saturation persisted into subsequent runoff events, ultimately resulting in significant reductions in total P concentrations in runoff.

There exists considerable trepidation with recommending tillage for any reason, largely because, even today, there remain substantial hurdles facing soil conservation that are perceived as being reinforced by messages that proclaim the virtues of tillage. Furthermore, a recommendation to cultivate soils to mitigate soil P sorption saturation concerns is not purely straightforward. Presumably this is best accomplished through a combination of inversion tillage (mold board) to draw subsoil to the surface combined with vertical tillage or disking to thoroughly mix soil within the plow depth. For extreme sites, the depth of tillage may be a problem. For instance, in some cases soil P sorption saturation is so extensive in the soil profile that tillage may not work, such as in the case of Han et al. [15] who found that P leaching was not diminished with simulated tillage, likely due to the persistence of a significant source of P below the tillage depth.

Alternatively, shallow cases of vertical stratification may be adequately mixed with disking alone. Due to the deleterious impact of tillage on soil health, only periodic tillage should be recommended. Finally, mitigation should focus on critical source areas and not all sites with vertical stratification.

### P Sorption Saturation Thresholds

The identification of environmental thresholds for soil P sorption saturation is a compelling objective that has many adherents. However, the assignment of these thresholds can be

difficult and controversial. Only in the Netherlands is a threshold used to regulate agricultural P applications to soils (0.25 assuming an  $\alpha$  of 0.5, based upon acid ammonium oxalate extraction of P, Fe, and Al). The limited use of environmental thresholds reflects, in part, fundamental and correct observations that greater P sorption saturation of soils that are neither hydrologically active, nor hydrologically connected to stream networks, does not require the same management as soils that are prone to runoff and have a high probability of P delivery to riverine systems [61].

Early research with soil P sorption saturation in the USA, particularly research focused on relationships with P in leachate or indicators of P desorption, such as water-extractable P, often identified non-linear relationships that included inflection points that could be used as thresholds for P sorption saturation. For instance, Maguire and Sims [31] reported P sorption saturation thresholds of 0.2 (Mehlich-3-extractable cation estimation) with dissolved P concentrations in leachate, above which the dissolved P concentrations increased with P sorption saturation at a statistically greater rate (Fig. 3).

When change points or other distinguishing quantitative features are not apparent, such is often the case with overland flow, then off-site factors affecting water quality and system response enter into consideration. At one time, a dissolved P concentration of 1 mg/L was proposed as a non-point source runoff threshold, as wastewater treatment plants in the USA were held to this standard [7]. This proposal was used to assess P sorption saturation through its relationship with dissolved P in runoff water or P in water-extractable soil P, but has not gained traction. Tying P sorption saturation thresholds obtained from soil samples to downstream water quality outcomes requires scaling exercises that consider many processes along the flow pathway. As a result, adoption of precedents, such as the Netherlands regulation or change points in the dissolved P/leachate P relationship, currently represents the most compelling approach to identifying environmental thresholds.

One implication of a threshold in P sorption saturation is that it can be used not only as a test for current application of fertilizers and manures but also as a gauge for planning to determine how much more P loading a soil can be expected to receive before P desorption rises to an environmental concern. Nair et al. [42] derived P sorption saturation thresholds for surface and subsurface horizons of sandy soils in Florida by identifying change points in the relationship between water-extractable P and P sorption saturation. These thresholds were then used to determine the Soil P Storage Capacity [40], a metric of the remaining P sorption capacity of a soil prior to reaching the P sorption saturation threshold. By determining the Soil P Storage Capacity metric of multiple horizons, they were able to forecast the sorption potential of the entire solum, an important consideration in Florida where rising water tables mobilize weakly bound forms of P in soil.

This was extended to forecast the potential of wetlands receiving agricultural runoff to store intercepted P, highlighting the implications of the Soil P Storage Capacity approach to watershed planning [41]. Certainly, such approaches hold great promise but will require wholesale adoption of P sorption saturation to achieve their potential.

## Conclusions

Soil P sorption saturation is clearly an excellent indicator of dissolved P concentrations in runoff water (surface and subsurface), but not the only indicator. If it is to be applied widely and systematically, programs must address how soils will be sampled, how soil P sorption saturation will be measured given the limitations of different soil testing approaches, and how thresholds are determined. These are all topics that have been addressed in various contexts and therefore can certainly be addressed. Better linking soil P saturation to agronomic recommendations will greatly expand the use of this measure. It is most likely, however, that a more narrow form of adoption of soil P sorption saturation will unfold, as has been the unfortunately piecemeal history of soil testing.

Regardless of how soil P sorption saturation is assessed, as a phenomenon, there is a need to address the environmental consequences of highly P-saturated soils. Most notably, soil P sorption saturation is responsible for the stubborn problem of legacy P. Mitigating this problem is not without trade-offs. An obvious, initial approach is to prevent the accumulation of P in hydrologically active and connected soils, preferably using environmental thresholds to limit fertilization (as opposed to agronomic thresholds). Alternatively, experience with the use of manure amendments suggests that the addition of P along with an amendment to increase the P sorption capacity of a soil can reduce dissolved P losses. The latter strategy involves some unknown outcomes, including the unintended consequence of potential increasing organic P mobility.

For hydrologically active and connected soils that have high levels of P sorption saturation (i.e., critical source areas of watershed P loss), short- and long-term mitigation options do exist. Again, all options involve trade-offs. One short-term option is to perform a single tillage event with the objective of bringing P sorption capacity from the subsoil to the surface and mixing surface soil to dilute sorbed P and to sorb P in solution. Here, there are both agronomic and soil conservation consequences to weigh. Other options include the judicious use of P sorbing amendments, either with land-applied manures or directly to soil. Again, targeting zones that control P loss to runoff water is critical to the effectiveness of these strategies. Over the longer term, phytomining approaches should be implemented.

## Compliance with Ethical Standards

**Conflict of Interest** The corresponding author states that there is no conflict of interest.

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