A phosphorus sorption index and its use to estimate leaching of dissolved phosphorus from agricultural soils in Ontario

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ABSTRACT

Compared with soil testing phosphorus (STP), such as Olsen P, the degree of P saturation (DPS) generally improves the risk prediction for soil P loss. This study was conducted to assess various P sorption indices (PSI) to indicate P sorption maximum (Q_{max}) of soils, and their derived DPS indices as indicators of dissolved reactive P (DRP) concentration in soil leachate. A total of 236 intact soil columns were collected for leaching experiments from six major soil series in Ontario. By conducting the single-point isotherm, PSI-a of a given soil was determined as the amount of P sorbed by the soil during 24-h shaking in the 60 mg P L^{-1} solution, PSI-b as the quotient of PSI-a/log C, where C is the solution P concentration after 24-h shaking, and PSI-c as the sum of PSI-a and Olsen P concentration. Among the tested PSIs, PSI-c gave the best prediction of Q_{max}. Compared to Olsen P, soil DPS-1 (i.e. the quotient of Olsen P/PSI-c) improved the prediction of leachate DRP concentration. Moreover, soil pH did not impact the relationship of DPS-1 vs. soluble soil P loss. Based on the results from conditional probability analyses, Ontario soils were grouped into no risk, low risk, medium risk, and high risk categories. Considering that Olsen P is the current agronomic STP in Ontario and PSI-c can be quickly determined, soil DPS-1 can be used to identify leaching P loss and/or combined with site hydrology and P management practices for a more comprehensive soil P loss assessment.

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1. Introduction

With increasing concerns over eutrophication of surface waters by agricultural P losses, the demand for using simple soil P measures to assess soil P loss potential has increased rapidly (Sharpley et al., 2011; Sims et al., 2000). It has been suggested that some existing soil P tests originally developed for agronomic purposes can function well to represent soil P loss potential (Sims et al., 2000), and that soils with extremely high concentrations of soil test P (STP) are more at risk and require more intensive management (Sharpley et al., 2011; Sims et al., 2002). However, studies have also indicated that STP concentration alone might lead to erroneous assessment of soil P loss potential, particularly when soils have contrasting chemical and mineralogical properties. For example, Sharpley (1995) showed that two soils with 200 mg Mehlich-3 P kg^{-1} produced runoff water with dissolved reactive P (DRP) concentration of 0.28 mg L^{-1} and 1.36 mg L^{-1}, respectively. To better predict P loss potential in such cases, the degree of P saturation (DPS) has been suggested because it not only considers amounts of sorbed P

in a soil but also takes into account the total amount of P sorption sites present in the soil (Sharpley, 1995; Sims et al., 2002).

The original DPS concept is based on the idea of P being bounded by reactive oxides of Al and Fe in non-calcareous sandy soils, which can be extracted by a solution of oxalic acid and ammonium oxalate having pH = 3 (Schoumans, 2009). In intensive livestock production areas of the Netherlands, a DPS of 25% determined using oxalate extractable Al, Fe, and P has been established as the critical value, above which the potential for P movement into surface and ground waters becomes unacceptable. This approach, however, is not commonly performed by soil testing laboratories in North America (Schoumans, 2009; Sharpley et al., 2011). Alternatively, the DPS in acidic soils can also be reliably estimated from Mehlich-3 extractable Al, Fe, and P (Beauchemin and Simard, 1999; Sharpley et al., 2011). In calcareous soils, the ratio of Mehlich-3 P/Mehlich-3 Ca was a better measure of soil DPS than that of Mehlich-3 P/(Mehlich-3 Al + Fe) (Ige et al., 2005; Kleinman and Sharpley, 2002). Most agricultural soils of Ontario are neutral and calcareous in origin, but some of them are becoming increasingly acidic in recent years, mainly caused by nitrogen fertilizer application (Bates and Johnston, 1991). Based on a total of 391 soil samples covering most agricultural areas of Ontario, soil pH ranges between 4.2 and 7.6 (Wang et al., 2010, 2015). For such soils with a wide range of pH, the ratio of Mehlich-3 P/(Mehlich-3 Al + Fe) had an overall close

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relationship with potential soil P loss; the overall relationship, however, tended to overestimate P loss from alkaline soils (Wang et al., 2010, 2015). Thus, there is a need to develop a soil DPS measure which can be easily determined and consistently and efficiently represent the risk for soil P loss regardless of soil pH levels.

Another commonly-used measure of soil DPS is the ratio of a STP (e.g., Olsen P), representing the amount of P sorbed in the soil, to P sorption maximum (Q_{max}) of the soil, which can be identified by multi-point P sorption curves (i.e. Langmuir equation) (Sharpley, 1995). It should be noted that the Q_{max} determined using Langmuir equation often does not represent true P sorption maximum in reality; these values, however, are convenient to work with and can better reflect relative P sorption maximum among soils. Attaining the curves is a time-consuming process and thus unlikely to be an economically viable routine soil testing procedure. As such, a soil P sorption index (PSI), determined using a single-point sorption assessment, has been developed and suggested as a quick and reliable estimate of soil Q_{max}, particularly for calcareous soils (Bache and Williams, 1971; Allen et al., 2006; Zhou and Li, 2001). Soil PSI was initially calculated as a quotient of sorbed P (i.e. the difference between the amounts of P added to the soil and P in solution after a certain time period of shaking) divided by the logarithm of the solution P concentration after shaking (Bache and Williams, 1971). Such a method has been followed by many researchers to determine soil PSI (hereafter referred to PSI-b) (Mozaffari and Sims, 1994; Eghball et al., 1996; Sims, 2000b). Accordingly, the quotient of STP/PSI-b as a soil DPS index has often been assessed to predict soil P loss potential. For example, a good linear relationship was found between Olsen P/PSI-b and runoff DRP concentration from calcareous soils (Westermann et al., 2001). One shortcoming with PSI-b is that it is difficult to explain its physical significance. In the current literature, some researchers directly used the amount of P sorbed by a given soil as soil PSI value, referred to as PSI-a in this study, ignoring the solution P concentration (Sims, 2000b). Meanwhile, some researchers used the sum of PSI-a and a STP, referred to as PSI-c, as a measure of soil Q_{max} when calculating soil DPS indices. For instance, Allen et al. (2006) reported that the quotient of STP/(STP + PSI-a) was significantly related to runoff DRP concentration in a quadratic manner. Compared to PSI-a, PSI-c includes amount of P previously sorbed in the soil and may thus better represent total amount of P sorption sites present in the soil. Currently, limited information is available on which PSI better represents soil Q_{max}.

Soil PSI measures generally reflect the combined contribution of various soil factors (e.g., clay content, clay mineralogy, organic matter content, exchangeable Al, Fe, and Ca concentrations, and soil pH) to P sorption capacity (Tisdale et al., 1993), and thus may apply to various soils. For a certain region, it may be advantageous to use a reliable agronomic STP for that region to estimate amount of P present in the soil, since the STP likely gives a good approximation of sorbed P across the soil types found in the region (Sims et al., 2000). In addition, from a soil testing perspective, such an agronomic STP is likely a method that is suitable for commercial laboratories. We hypothesized that the ratio of Olsen P (i.e. current agronomic STP in Ontario) to a PSI is a promising DPS measure for various Ontario soils and can potentially be a reliable indicator of soil P loss with a wide range of pH.

This study was conducted to identify a soil PSI best correlated with Q_{max} for Ontario soils, and to comprehensively evaluate its derived soil DPS indices to indicate DRP concentration in soil column leachate, with an emphasis on the impact of pH on the risk identification of soil P loss. This study is complementary to our published work (Wang et al., 2012), where we evaluated the relationships between leachate DRP concentration and commonly-used STP measures and the DPS indices calculated based on Mehlich-3 extractable P, Al, and Fe. Both studies provide data-based evidence, which, along with regional preference, efficiency of operation, and ease of implementation, would help Ontario establish an appropriate environmental soil P test to represent the risk of soil P loss in the new P index of the province.

2. Materials and methods

2.1. Soil selection and sample collection

The six soil series selected as representative types in the livestock production areas of Ontario, Canada, were classified according to the U.S. Soil Taxonomy (Soil Survey Staff, 1999). The soils included a Brookston clay (BC, a Typic Argiaquoll), a Perth clay loam (PCL, an Aquic Hapludalf), a Conestogo loam (CL, a Typic Eutrochrept), a Grenville loam (GL, a. Typic Eutrochrept), a Listowel silt loam (LSL, a Typic Hapludalf), and a Fox sandy loam (FSL, a Typic Hapludalf). For each soil series, existing soil test data (collected from farmers, researchers, and extension professionals) were used to select sites covering a wide range of soil test P concentrations. A total of 10 sites were chosen for each soil series, except for the Brookston clay, which had nine sites. In this paper, each field site was referred to Z-i with Z representing soil type (i.e., BC, PCL, CL, GL, LSL, and FSL) and i denoting the sampling site number (i.e., 1, 2, 3, ..., 10). The selected field sites were mainly used for growing corn (Zea mays L.), soybean (Glycine max (L.) Merr.), alfalfa (Medicago sativa L.), wheat (Triticum aestivum L.), and barley (Hordeum vulgare L.), which are the predominant crops grown in Ontario. At each site in the spring of 2007 (before any spring fertilization, tillage, or planting operations), four undisturbed soil columns (15-cm i.d., 20-cm depth) were sampled by driving polyvinylchloride (PVC) pipes (with the bottom edge beveled) into the ground. At the time of column collection, a bulk soil sample (approximately 150 kg) of 0 to 20 cm was collected from the area with the radius of approximately 10 m, where soil columns were also collected for each field site. Two subsamples were taken from each bulk soil sample and were then ground to pass a 2-mm sieve, with one analyzed for soil pH, organic carbon, particle size distribution, water extractable P (WEP), and Mehlich-3 extractable P, Al, Fe, and Ca, and the other for soil PSI, P sorption curve, and Olsen P.

2.2. Soil P analyses and DPS determinations

Soil pH was measured using the electrode approach after shaking 10 g soil in 10 mL distilled water (Thomas, 1996). Soil organic carbon was determined using a dry combustion method with a Leco CN2000 (Leco Corporation, St. Joseph, Michigan) analyzer (Nelson and Sommers, 1996). Particle size distribution was determined using a hydrometer method (Kroetsch and Wang, 2008). Soil test P measures and related chemical properties determined included: (i) Olsen P (shaking 2.5 g soil in 50 mL of 0.5 M NaHCO₃ (pH = 8.5) solution for 30 min; Sims, 2000a); (ii) WEP (shaking 2 g soil in 20 mL of distilled water for 1 h; Self-Davis et al., 2000); and (iii) Mehlich-3 P, Al, Fe, and Ca (shaking 2.0 g soil in 20 mL of the extracting solution for 5-min; Sims, 2000c).

Soil PSI indices were determined using a single-point P sorption isotherm (Bache and Williams, 1971). A 1.0-g dry soil sample was weighed into a 50-mL centrifuge tube and 25 mL of 0.03 M KCl solution containing 60 mg P L^{-1} was added. The suspension was shaken for 24 h at room temperature using an end-to-end shaker. The samples were then centrifuged and filtered through a 0.45-μm filter. Various soil PSIs were calculated as follows:

$$PSI\text{-}a = \frac{(60-C) \times 0.025}{0.001} \tag{1}$$

$$PSI\text{-}b = \frac{PSI\text{-}a}{\log C} \tag{2}$$

$$PSI\text{-}c = PSI\text{-}a + Olsen\ P \tag{3}$$

where C = P concentration in the solution after 24-h shaking (mg L^{-1}). The units for PSI-a, PSI-b, and PSI-c were mg kg^{-1}, L kg^{-1}, and mg kg^{-1}, respectively.