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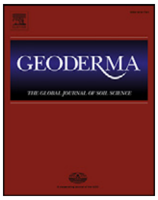

Agronomic and environmental soil phosphorus tests for predicting potential phosphorus loss from Ontario soils

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ABSTRACT

There has been an increased research interest towards developing appropriate environmental soil P tests for identifying soils sufficiently high in P to be of concern to water quality. The objectives of this study were to evaluate the relationships between various soil test P (STP) measures, and to assess the suitability of these STPs and derived indices of degree of P saturation (DPS) as indicators of soluble P losses (assessed as water extractable P (WEP)) from Ontario soils. A total of 391 surface (0–20 cm) soil samples were collected across the province to represent the diverse physical and chemical properties of agricultural soils in Ontario. Significant relationships were generally found between the tested STPs. Among all measured STPs and DPSs, soil Fe-oxide coated filter paper strip P (FeO-P) and DPS_{OI} (Olsen-P/(Olsen-P + PSI)) had the strongest non-linear relationships with soil WEP concentration (r^2 values of 0.88 and 0.82, respectively), suggesting these measures may be useful as indicators of soil P losses for Ontario soils. The soil WEP concentrations were significantly correlated to P extractable by the Olsen and the Mehlich-3 methods ($r^2 = 0.72$ for both extractants). In addition, DPS_{M3}-2 (Mehlich-3 P)/(Mehlich-3 Al + Mehlich-3 Fe) and DPS_{M3}-3 [Mehlich-3 P/(Mehlich-3 Al)] were highly promising indicators of soil P losses for agricultural soils in Ontario.

1. Introduction

Intensification of livestock operations in developed countries over the last few decades has led to the production of large and localized volumes of manure (Sharpley et al., 2004; Maguire et al., 2007; Sims et al., 2000). Application of animal manures to meet the nitrogen requirements for crop growth is a practice that has resulted in excess phosphorus (P) applications and build-up in soils (Leytem et al., 2006). In Ontario, it has been estimated that over 70% of agricultural soils contain adequate to excessive levels of soil test P (Fixen et al., 2010). Elevations in soil P levels can be directly related to the increased potential of soil P loss and thus contributing to eutrophication of surface water (Sims et al., 2000; Sharpley et al., 1996). As a result, there has been an increased research effort worldwide towards developing appropriate environmental soil P tests for identifying soils that are at risk of P losses causing concerns to water quality.

Some agronomic soil P tests (e.g., Olsen-P, Mehlich-3 P, and Bray-1 P), either alone or as an important component of a P index, have been recommended for assessing the risk for soil P loss (Sims et al., 2000). Such P tests, however, were developed to determine the amounts of P that would be available to a crop during the growing season, and may not adequately reflect soil P losses during an episodic events such as rainfall or snowmelt (Allen et al., 2006; Torbert et al., 2002). Soil water extractable P (WEP), Fe-oxide coated filter paper strip P (FeO-P) and various soil P saturation estimations have been proposed to represent the potential for soil P losses due to their strong theoretical foundations for fulfilling risk evaluation (Sharpley, 1993; Breeuwsma and Silva, 1992; Pote et al., 1999).

Selection of an appropriate environmental soil P test for a region should rely on a variety of field experiments (i.e., watershed monitoring and field runoff plots) and/or indoor rainfall simulations with runoff boxes and intact soil columns (Guidry et al., 2006; Kleinman et al., 2004). However, such experimental techniques are time-consuming and labor intensive. Of the various STP methods available, studies conducted in Ontario and beyond have shown that soil WEP is most consistently and highly correlated with dissolved reactive P (DRP) concentrations in surface runoff (Pote et al., 1999; Penn et al., 2006; Wang et al., 2010). This is probably due to the fact that the extracting solution for WEP is the closest to the rainfall water in terms of the ability of releasing P from soil components (Penn et al., 2006). Therefore, the strength of the relationships between agronomic STP or the derived

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DPS and WEP may to some degree reflect the suitability of these soil P measures as indicators of soil P loss. In fact, many researchers use soil WEP as a surrogate of soil P losses to evaluate the suitability of various STPs and DPSs as indicators of soil P losses (Khiari et al., 2000; Nair et al., 2004; Ige et al., 2005). In order to cost effectively identify a scientifically sound environmental soil P test for a given jurisdictional region, the relationship between various STPs or DPSs and soil WEP should be evaluated across a sufficiently large population of soils from the area in question. The most promising methods should then be further assessed with field and/or indoor simulation studies at a relative small scale. Such analyses would improve our understanding of the relationships between various STP or DPS and soil P loss into surface water at a regional level. A comparison between analyses of a large population of soils and results from field and/or indoor studies of a relatively small scale may show how suitable various STPs and DPSs are for predicting potential soil P losses across this region. Moreover, the comparison would indicate if there is a need to conduct further field/indoor rainfall simulation studies with a wider range of soils. Implicit in the above is the understanding that estimation of a soil's capability to release P to runoff or leaching waters is primarily only the assessment of the source component of a typical P index unless specific P loss relationships are observed for soil types (i.e. say based on textural differences) that would also potentially affect transport mechanisms of P as well.

Ideally, a soil P test method would identify both the soil P status for risk of loss as well as provide an agronomic basis for P application under local conditions. Some forms of STP and DPS may therefore be preferred when assessing the risk of P loss from soils, if they also provide relevant agronomic information. Alternatively, some predominantly environmental soil P tests may also be suitable agronomic tests. However, often little information is available regarding the suitability of predominantly environmental STPs and DPSs for identifying crop requirements for P fertilization. There have been some reports on close relationships between soil P extracted by Mehlich-3, Olsen, Bray-1, and FeO extractants (Menon et al., 1997; Kleinman et al., 2001; Wolf and Baker, 1985; Atia and Mallarino, 2002). Bates (1990) found that soil Olsen P was significantly correlated with other STPs following the order of Mehlich-3 P, Bray-2 P, and Bray-1 P for 88 Ontario soils, although Olsen P was superior for predicting P uptake by test plants. In addition, continuous manure additions not only increase P levels in surface soils but may also change soil P chemistry (i.e. increasing pH and changes in P forms present in soils), which suggests a need to re-evaluate the suitability of various soil P testing methods and their relationships in soils following long periods of manure application (Sharpley et al., 2004).

The objectives of this study were (i) to evaluate the relationships between various STPs (i.e., soil Olsen P, Mehlich-3 P, Bray-1 P, and FeO-P), and (ii) to assess the suitability of these STPs and the derived DPSs as indicators of soil P losses based on their relationships with soil soluble P (WEP) as a preliminary step for identifying potential environmental indices that could be applicable to Ontario soils.

2. Materials and methods

2.1. Soil collection

A total of 391 soil samples (0–20 cm) collected across the province of Ontario were analyzed in this study. Among them, 60 soil samples representing six major soil types in the livestock production areas of Ontario were used for the runoff rainfall simulations and leaching studies, as described by Wang et al. (2010, 2012). An additional 138 soil samples collected by Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) and the A&L Canada Laboratories Inc. came from 30 of 49 census divisions of Ontario accounting for 88.3%, 85.7%, 99.6%, and 95.2% of Ontario's crop lands, cattle, pig, and poultry (excluding turkeys) productions, respectively, based on 2011 Census of Canada. The remaining 193 soil samples were also collected across Ontario by OMAFRA and the A&L Canada Laboratories Inc., but specific information as to farm location was not available. These 391 soil samples covered most agricultural areas of Ontario and provided a wide range of STP, pH, textural class, and organic carbon (Table 1). All soil samples were air-dried, ground to pass a 2-mm sieve, and analyzed as described below.

2.2. Determination of soil physical and chemical properties

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 (Sims, 2000d); (ii) saturated iron-oxide strip extractable P (FeO-P) (Chardon, 2000); (iii) water extractable P (WEP) (Self-Davis et al., 2000); (iv) 0.01 M $CaCl_2$ extractable P (Self-Davis et al., 2000); (v) Bray-1 P (Sims, 2000a); and (vi) Mehlich-3 P, Al, and Fe (Sims, 2000b).

A soil P sorption index (PSI) (Sims, 2000c) was used as a simple estimation of soil P sorption capacity (Bache and Williams, 1971). Approximately 1.0 g dry soil sample was weighed into a 50-mL centrifuge tube, and 20 mL of solution containing 75 mg P L^{-1} in distilled water was added. The suspension was shaken for 18 h at room temperature using an end to end shaker. The samples were then centrifuged for 30 min and the supernatant filtered through a 0.45-μm filter. The PSI was then calculated as follows,

$$\mathrm{PSI}\left(\mathrm{L\ kg^{-1}}\right) = X/\log C \tag{1}$$

where X = P sorbed from the equilibrating solution (mg P kg^{-1}) (i.e., (75 mg P L^{-1} − C) × 0.020 L/0.001 kg); and C═P concentration at equilibrium (mg L^{-1}).

The various DPS values were calculated as follows:

$$\mathrm{DPS_{M3}\text{-}1}(\%) = \text{Mehlich-3 P}/(\text{Mehlich-3 P} + \mathrm{PSI}) \times 100 \tag{2}$$

$$\begin{aligned}\mathrm{DPS_{M3}\text{-}2}(\%) = {} & \text{Mehlich-3 P}/(\text{Mehlich-3 Al} + \text{Fe}) \\ & \times 100,\ \text{on a molar basis}\end{aligned} \tag{3}$$

$$\mathrm{DPS_{M3}\text{-}3}(\%) = \text{Mehlich-3 P}/\text{Mehlich-3 Al} \times 100,\ \text{on a molar basis} \tag{4}$$

$$\mathrm{DPS_{Ol}}(\%) = \text{Olsen P}/(\text{Olsen P} + \mathrm{PSI}) \times 100 \tag{5}$$

$$\mathrm{DPS_{Bray}}(\%) = \text{Bray-1 P}/(\text{Bray-1 P} + \mathrm{PSI}) \times 100 \tag{6}$$

$$\mathrm{DPS_{FeO}}(\%) = \text{FeO-P}/(\text{FeO-P} + \mathrm{PSI}) \times 100. \tag{7}$$

All determinations for P were conducted using a Flow Injection Auto-Analyzer (QuikChem FIA +8000 series, Lachat Instruments, Loveland, CO, USA) with the ammonium molybdate ascorbic acid reduction method of Murphy and Riley (1962). Concentrations of Fe and Al were determined using an atomic adsorption spectrometer (PerkinElmer, CT, USA).

2.3. Data analysis

All statistical analyses were performed using the SAS program (SAS Institute Inc., 2002). Quadratic regression analyses between various measures of soil extractable P and measurements of DPS were performed