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Phosphorus source coefficient determination for quantifying phosphorus loss risk of various animal manures

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ABSTRACT

Quantification of phosphorus (P) loss risk of animal manures is essential to scientifically sound P risk assessment and environmental friendly nutrient management, but has faced significant challenges due to the shortage of appropriate techniques. This study was conducted to determine P source coefficients (PSC) for quantifying differential P loss risk of various manures relative to soluble chemical fertilizer. After 2-d, 2-week, 8-week, and 26-week soil incubations with various manures, P-amended soils were analyzed for Olsen P (Ol), Mehlich-3 P (M3), water extractable P (WEP), and Fe-oxide coated filter paper strip P (FeO), each of which was then used to calculate manure PSC. Manure PSC_{M3} had the strongest linear relationships ($r^2 = 0.95$–0.97) among different incubation durations, compared with PSC_{WEP} ($r^2 = 0.79$–0.91), PSC_{Ol} ($r^2 = 0.85$–0.94), and PSC_{FeO} ($r^2 = 0.88$–0.91). The 2 week incubation yielded PSC_{M3}which had the strongest linear relationships ($r^2 = 0.87$–0.97 with a mean of 0.95) among the tested soils, compared with those from 2-d, 8-week, and 26-week incubations. In addition, laboratory PSC_{M3} had the strongest linear relationships with those PSC_{M3} measured under field conditions, relative to PSC_{Ol}, PSC_{FeO}, and PSC_{WEP}. Hence, the 2-week incubation along with Mehlich-3 P yielded the most consistent PSCs for various manures across soil types, incubation durations, and soil conditions, and can be recommended as a common protocol for determining manure PSC. The recommended default PSC values are 110, 65, 46, and 43% for liquid swine, liquid dairy, solid poultry, and solid beef manures, respectively, for the new P index of Ontario.

1. Introduction

Modern agriculture, with its greatly enhanced yield, relies on the expanded use of supplemental P fertilizers. With rising global demand for food, particularly for meat, to feed growing human population, it is anticipated that P demand for crop production will be increasing through the middle of the century (Cordell et al., 2009; Gilbert, 2009). Various estimations have indicated that global rock phosphate reserves could be depleted in 50–225 years (Gilbert, 2009). Hence, animal manure is increasingly being recognized for its enormous potential as an alternative P source (Gilbert, 2009). In 2007, for example, the USA produced 1.8 Tg P in animal manure (USEPA, 2014). In the past decades, however, continuous long term P applications as manure or commercial P fertilizer, often in excess of crop demand, have created situations, where further P application would increase dramatically P losses, contributing to eutrophication of surface waters (Sims et al., 2000; Wang et al., 2015). Such water quality deterioration is particularly severe in intensive livestock regions (Sims et al., 2000). Therefore, effects of manure P application on soil P loss potential have to be accounted for in the P index, an applied assessment tool widely used to identify agricultural fields most vulnerable to P loss by accounting for the major source and transport factors controlling P movement (Shober and Sims, 2007; Sharpley et al., 2012).

Forms and concentration of P in animal manure are influenced by animal types, diet, treatment, and storage, with inorganic P accounting for 21–90% of total P in manure (Barnett, 1994; Sharpley and Moyer, 2000; Peirce et al., 2013; Li et al., 2014). Accordingly, manure P availability or solubility for transport to surface water varies with manures after land application (Sharpley and Moyer, 2000; Kleinman et al., 2002). Currently, P source coefficients (PSC) are often used to differentiate various manures for their relative potential for release of manure P applied to the soil into runoff in the calculations of the P index (Leytem et al., 2004; Elliott et al., 2006; Smith et al., 2009). One of the on-going efforts towards to developing a new P index for Ontario, Canada, is to determine PSC values for the major animal manures in the province.

Various methods have been suggested to calculate manure PSC, including manure water extractions, rainfall simulation studies comparing runoff dissolved reactive P with P source water extractable P (WEP), and soil incubation studies (Shober and Sims, 2007). Compared with the first two methods, the incubation method proposed by Leytem et al. (2004) has the potential to account for differences in P solubility

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when manures are allowed to equilibrate with the soil for a period of time (Smith et al., 2009), which is often the case for P losses related with manure application. In the incubation study, manure PSC is calculated by dividing the extractability (i.e., the percentage of total applied P extracted by STP extractants after a period of incubation) of manure P by that of inorganic-P (Leytem et al., 2004). Such PSC could provide a good predictor of the relative risk of P transport after manure application (Smith et al., 2009).

Previous studies have shown that manure PSC values varied with STP method employed, incubation duration, and soil type (Leytem et al., 2004; Smith et al., 2009). Such findings have raised questions on what combination of STP method and incubation duration should be used, so that the derived PSC can most efficiently and consistently differentiate various manures in different soils. Currently, the selection of STP method and incubation duration is only based on professional judgement and lacks science-based validation. This study aimed to identify appropriate STP methods and incubation lengths which can give various manures reasonably consistent PSC values across a range of soils. In addition, we assessed the relationships between manure PSC values and manure and soil properties, and recommended the default PSC values for major manure types in Ontario, Canada.

2. Materials and methods

2.1. Sample collection and preparation

Six soils, including a Brookston clay (BC, Typic Argiaquoll), a Perth clay loam (PCL, Aquic Hapludalfs), a Conestogo loam (CL, Typic Eutrochrepts), a Grenville loam (GL, Typic Eutrochrepts), a Listowel silt loam (LSL, Typic Hapludalf), and a Fox sandy loam (FSL, Typic Hapludalf), were selected as representatives covering a great range of chemical and physical properties. For each soil, a bulk soil sample (0–20 cm) of approximately 150 kg was collected in the spring of 2007 before fertilizer, manure, and/or any other amendment application and planting. Part of each bulk sample was air-dried and passed through a 2-mm sieve for the incubation study and analysis. Selected physical and chemical properties of soils are presented in the Table 1.

Four manures were used in this study including solid beef manure (SB), liquid dairy manure (LD), liquid swine manure (LS), and solid poultry manure (SP). Three different sources of each manure were collected from the major manure production areas of Ontario, including Huron (SB-1), Wellington (SB-2), and Stormont (SB-3) for SB manure; Perth (LD-1), Oxford (LD-2), and Oxford (LD-3) for LD manure; Huron (LS-1), Oxford (LS-2), and Essex (LS-3) for LS manure; and Huron (SP-1), Niagara (SP-2), and Wellington (SP-3) for SP manure. One composite sample was collected from each manure source farm.

2.2. Laboratory incubation study

Each manure source was incorporated into 260 g of each of the six soils at a rate of 61.5 mg P kg^{-1} dry soil, equivalent to approximately 120 kg P ha^{-1}(soil bulk density = 1.3 g mL^{-1} in the 0–15 cm soil depth), which is representative of P application rates when manures are applied to meet N requirements of the dominant field crops (i.e. corn, wheat, etc.) in Ontario. An inorganic P source (KH_2PO_4) was applied at the same rate to represent commercial P fertilizer. A zero-P control was used for each soil. After incorporation, the soils were incubated in the glass containers (8-cm i.d., 6.5-cm depth) at room temperature (25 ± 2 °C) of a greenhouse under controlled-environment. Each container was covered with Parafilm, with two holes drilled to allow gas exchange and maintain aerobic conditions during the incubation. Soil water content was maintained at 75% of soil water holding capacity by adding distilled water at a weekly interval. Soil water holding capacity was determined by drying the soil for 24 h at 105 °C after saturating a soil core (5-cm i.d., 12-cm depth, soil bulk density = 1.3 g mL^{-1}) packed with the air-dried soil and then leaving it to freely drain for 2 d. The calculated gravimetric moisture content (n = 2) at soil water holding capacity was 41.6, 40.7, 32.6, 48.9, 36.8, and 41.3% for BC, CL, FSL, GL, LSL, and PCL soils, respectively. The incubation experiment was arranged in a completely randomized design with four replicates.

Soil samples were collected at 2-d, 2-weeks, 8-weeks, and 26-weeks after the initiation of the incubation. In order to avoid any possible destructions that soil sampling may cause to the incubated soil, a total of four sets were prepared for the entire experimental units, so that one set can be harvested at each sampling date, i.e., 2-d, 2-weeks, 8-weeks, and 26-weeks, respectively, after the initiation of the incubation. There were a total of 1344 experimental units.

2.3. Field incubation study

In order to validate the results obtained from laboratory studies under natural conditions, a field incubation study was conducted at the Research Farm of Harrow Research and Development Center of Agriculture and Agri-Food Canada, Harrow, Ontario, Canada, from May to November 2008. Three types of soils with a range of soil textures were selected for the field incubation study, including BC and FSL soils, which were also used for the laboratory incubation study, and an Embro silt loam (ESL, Typic Hapludalfs), which has highly similar soil properties to the LSL soil (Table 1). As such, it is reasonable to compare the PSC values obtained from field incubation study to those from laboratory incubation studies. Four types of manure, with one source for each, and an inorganic-P source (KH_2PO_4) were incorporated respectively into 13.78 kg of the selected soils at the same P rate as in the laboratory incubation. After thorough mixing with care, the soil was filled into a PVC column (30 cm i.d., 20 cm depth) by gradually hand-tapping to obtain the desired bulk density (1.3 g cm^{-3}). A zero-P control was included for each soil. The soil columns were buried in a field with the internal soil level aligned with the external soil surface to mimic the natural environment. The treatments were arranged in a completely randomized design with three replicates. At the beginning of the incubation, soil moisture was adjusted to reach 75% of soil water holding capacity. No additional manual moisture adjustment was carried out for the remaining time period of the season. No crops were grown during the experiment.

Table 1
Selected properties of the soils included in the study.

Soil types	pH	Sand	Silt	Clay	Organic C	Olsen P	WEP[a]	Mehlich-3 P	Mehlich-3 Ca	FeO-P[b]
		g kg^{-1}				mg kg^{-1}				
Brookston clay	6.3	383	279	338	23.0	20.5	2.6	38.9	2588	24.9
Conestogo loam	6.5	430	365	204	22.9	19.4	3.0	58.6	2758	28.8
Fox sandy loam	5.7	774	140	86	11.7	24.8	4.0	119.0	760	39.7
Grenville loam	6.7	532	284	184	53.7	11.0	0.9	22.9	5084	16.3
Listowel silt loam	7.3	344	459	197	29.0	8.3	1.0	11.9	3860	8.3
Perth clay loam	6.4	305	432	263	23.4	21.1	2.7	45.3	2881	25.0
Embro silt loam	7.9	356	487	157	25.0	26.6	–	–	–	–

[a] Water extractable P.
[b] Fe-oxide coated filter paper strip extractable P.