

Agri-environmental Thresholds using Mehlich III Soil Phosphorus Saturation Index for Vegetables in Histosols

Julie Guérin, Léon-Étienne Parent,* and Rahima Abdelhafid

ABSTRACT

The P concentration in Norton Creek which drains cultivated Histosols in Quebec showed median concentration exceeding up to 14 times the environmental guideline of 0.03 mg total P L⁻¹. The aim of this study was to develop environmental and agronomic thresholds using soil tests to provide a tool for P management in Histosols. Soil samples were collected from Histosols across Quebec (82) and in fertilizer trials (66) to calibrate soil test methods against the degree of P saturation (DPS_{OX}) using the acid-oxalate method and setting $\alpha_m = 0.4$, and the water-extractable P (P_W) (Sissin, 1971). The field trials on crop response to added P were conducted with carrots (8), potatoes (11), onions (10), Chinese cabbage (7), celery (10), and lettuce (20). Relative yields were computed as yield in control without P divided by highest yield with added P. The Mehlich III (M-III) P extraction was more closely related ($r^2 = 0.73$) to DPS_{OX} than the Bray 1 method ($r^2 = 0.62$) and the Florida extraction method ($r^2 = 0.53$). The [P/(Al+γFe)]_{M-III} ratio as index of P saturation (IPS_{M-III}) was the most closely related to DPS_{OX} ($r^2 = 0.88$) setting $\gamma = 5$. The critical [P/(Al+5Fe)]_{M-III} ratio of 0.05 at DPS_{OX} = 0.25 and P_W = 9.7 mg P L⁻¹ was validated by an independent study from North Carolina. The soil group (low- vs. high-IPS_{M-III} soils) significantly influenced crop response to added P. Critical agronomic IPS_{M-III} values were found between 0.10 and 0.15. Those environmental and agronomic benchmarks are instrumental for managing the P in vegetable-grown Histosols.

THE SUSTAINABLE P management of cultivated organic soils must take into account ecological impacts of the P fertilization on contiguous and global environment (Parent and Ilnicki, 2003). Cultivated Histosol areas are known to largely contribute to eutrophication of the Florida Everglades (Hortenstine and Forbes, 1972; Porter and Sanchez, 1992) and Lake Ontario (Nicholls and MacCrimmon, 1974; Miller 1979; Longabucco and Rafferty, 1989). Annual P losses were found to be in the range of 1 to 37 kg P ha⁻¹ in New York (Duxbury and Peverly, 1978), Massachusetts (Howes and Teal, 1995), and Ontario (Miller, 1979), but up to 168 kg P ha⁻¹ in the Everglades (Reddy, 1983).

Norton Creek, which drains Histosols used for vegetable production in Quebec, had poor water quality (0.28–0.60 mg total P L⁻¹), the median concentration exceeding 14 times the environmental guideline of 0.03 mg total P L⁻¹ (Simoneau, 1996). The P concentration in runoff is linked primarily to soil water-extractable P (P_W) (Pote et al., 1999). Runoff in cultivated bogs is generally low in P when small amounts of fertilizer are applied (Eck, 1990). Because dissolved P concentration

was nine times that of particulate P, runoff and leaching of fertilizer P applied in large amounts to vegetable crops were believed to be the major contributors to P pollution of Norton Creek (Simoneau, 1996). Hamilton and Bernier (1975) and Parent and Khiari (2003) reported no significant response of vegetables to added P in Quebec, thus indicating overfertilization, high mineralization rate of organic P, or limited P fixation capacity. Unpublished incubation data (Duguet, 2004) showed that net mineralization rate averaged only 0.063 mg P kg⁻¹ d⁻¹ during 150 d of incubation in Quebec Histosols.

Early work attributed P fixation in organic soils to Al and Fe compounds (Droughty, 1930; Kaila, 1959; Larsen et al., 1959; Wondrausch, 1969). The P losses from cultivated organic soils were thus related to amounts of Al and Fe compounds reacting with P (Miller, 1979; Porter and Sanchez, 1992; Efimov et al., 1996; Litaor et al., 2003). Oxy-hydroxides of Al and Fe contributing to P sorption in acid soils generally increase with C content (Williams et al., 1957). The Al-P forms were found to be more available to plants than Fe-P forms (Anthony and Ellis, 1968). Levesque and Schnitzer (1967) and Bloom (1981) confirmed the formation of metal-P complexes with organic matter. In general, fulvo-Fe phosphates represent a poor source of P for plant growth (Levesque, 1970) unless the organo-metallic complex is highly saturated with P (Levesque, 1969; Efimov et al., 1996). The Fe may accumulate in substantial amounts as limonite and goethite in organic soils, especially where the subsoil is sandy and facilitates water movement (Naucke et al., 1993). Okruszko et al. (1962) were the first to propose a soil test based on a molar ratio between P and (Al+Fe) in organic soil materials.

Dutch researchers (Van Der Zee et al., 1987; Breeuwsma and Silva, 1992) defined the degree of phosphate saturation as follows:

$$\text{DPS}_{\text{OX}} = \frac{P_{\text{OX}}}{\alpha_m (\text{Al}_{\text{OX}} + \text{Fe}_{\text{OX}})} \quad [1]$$

where α_m is the maximum saturation factor for total sorption (unitless) and P_{OX}, Al_{OX}, and Fe_{OX} are acid ammonium oxalate-extractable forms (mmol kg⁻¹). Selected values for α_m were 0.5 in Litaor et al. (2003) for Israel Histosols and 0.4 in Breeuwsma et al. (1986) across Dutch soils comprising two histic epipedons. A critical

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Abbreviations: α_m , maximum saturation factor; DPS, degree of phosphorus saturation; FBD, field bulk density; IPS, index of phosphorus saturation; γ , weighing coefficient for Mehlich III-extracted Fe; M-III, Mehlich III method; OX, acid ammonium oxalate method; P_{Bray1}, P extracted according to the Bray 1 method; PES, plasma emission spectroscopy; P_{Florida}, water-extracted P according to the Florida (Sanchez, 1990) method; P_W, water-extracted P according to Sissin (1971); RBD, reconstituted bulk density; VPDH, von Post degree of humification.

level for DPS_{OX} ($\alpha_m = 0.5$) was set at 0.25 corresponding to 0.10 mg ortho-P L^{-1} in the connecting groundwater of mineral soils (Breeuwsma and Silva, 1992).

Dissolved reactive P ($<0.45 \mu m$ filtration) in wells averaged 0.190 mg P L^{-1} in Israel Histosols showing DPS_{OX} ($\alpha_m = 0.5$) values of 0.065 ± 0.05 (Litaor et al., 2003). Litaor et al. (2003) attributed those high levels to recent P fertilization history combined with solute transport by preferential flow, although flushes of organo-metal-P complexes and mineralized organic P may also be involved. Prismatic or lump structure favorable to preferential flow has also been reported in temperate Histosols (Kuiper and Slager, 1963; Zeitz and Veltz, 2002). Because a period of 1 to 2 wk is necessary to achieve P sorption equilibrium state in high-Fe Histosols ($>49 g Fe_{OX} kg^{-1}$) (Efimov et al., 1996), P fertilizer should thus be applied in early spring and well before crack formation, and soil P should be maintained below a critical environmental P saturation level throughout the year as measures to prevent P loss.

The commonly used soil P tests for organic soils are the Bray 1 method in Michigan (Lucas, 1982) and water extraction in Florida (Sanchez, 1990). However, the routine soil test in Quebec and Mid-Atlantic USA is the multi-element Mehlich III (M-III) extraction method (Mehlich, 1984) followed by multi-elemental determination using plasma emission spectroscopy (PES). Quebec researchers (Khiari et al., 2000; Pellerin et al., 2006a) found that a DPS_{OX} of 0.25 in mineral soils ($\alpha_m = 0.5$) corresponded to a Sissingh (1971) P_W value of 9.7 mg P L^{-1} of soil. Because the M-III method (Mehlich, 1984) was found to be sensitive to soil texture (Giroux and Tran, 1985; Simard et al., 1991; Zheng et al., 2001) but not Sissingh (1971) P_W (Houba, 1986), Pellerin et al. (2006a) used that critical P_W value of 9.7 mg P L^{-1} to define critical index of P saturation using the M-III method (IPS_{M-III}) for four textural groups varying in clay content.

To account for the important role of amorphous Al and Fe in the retention and release of soil P, Sims et al. (2002) recommended the $(P/[Al+Fe])_{M-III}$ molar ratio (Mehlich, 1984) as an agri-environmental index for Mid-Atlantic USA. However, the M-III-extractable Fe was found to represent only 7 to 12% of (Al+Fe) on a molar basis in mineral soils (Khiari et al., 2000; Sims et al., 2002). In mineral soils containing 4 to 5% organic matter, the M-III method extracted 15 to 22% of oxalate Al compared to 2% of oxalate Fe (Khiari and Parent, 2005). Hence, the M-III-extractable Fe may require a weighing factor (γ) to account for extraction efficiency, especially in Histosols where Fe may be present in large quantities (Efimov et al., 1996).

The index of P saturation using the M-III method is thus defined as follows:

$$IPS_{M-III} = \frac{P_{M-III}}{Al_{M-III} + \gamma Fe_{M-III}} \quad [2]$$

where P_{M-III} , Al_{M-III} , and Fe_{M-III} are M-III-extractable forms (mmol kg^{-1}) and γ is a weighing coefficient for Fe. Khiari et al. (2000) and Pellerin et al. (2006a) used $\gamma = 0$ or 1 since the P_{M-III}/Al_{M-III} mass ratio and the $(P_{M-III})/$

$(Al_{M-III} + Fe_{M-III})$ molar ratio were closely related to each other. Sims et al. (2002) suggested to use $\gamma = 1$ to account for the role of Fe in P fixation in soils. However, γ has not been determined in high-Fe and high-C soils like organic soils.

A ratio expression reducing the effect of scooped soil density on soil test (Khiari et al., 1999) could be of significance in organic soils where bulk density is highly sensitive to soil preparation methods (Erviö, 1969; Van Lierop, 1981). Also, the tenfold increase in P extraction with the M-III compared to water extraction requires less sensitive analytical determination (Sanchez and Hanlon, 1990). As emphasized by Sanchez and Burdine (1988), there is a need to develop a soil P test related to P_W and reactive forms of Al and Fe to account for the high variability in soil P buffering capacities and make P fertilizer recommendations in Histosols.

The aims of the present study were (i) to calibrate an environmental $(P/[Al+\gamma Fe])_{M-III}$ molar ratio threshold after optimizing γ against P_W and DPS_{OX} in Histosols, and (ii) to determine agronomic $(P/[Al+\gamma Fe])_{M-III}$ thresholds for common vegetable crops grown on Histosols.

MATERIALS AND METHODS

Experimental Setup for Fertilizer Trials

During the 2002 to 2005 period, we conducted fertilizer P trials on eight carrot (*Daucus carota* L.), 10 celery (*Apium graveolens* L.), 11 potato (*Solanum tuberosum* L.), 10 onion (*Allium cepa* L.), 20 lettuce (*Lactuca sativa* L.), and seven Chinese cabbage (*Brassica rapa* var. *pekinensis*) commercial sites in organic soils of southwestern Quebec, Canada. Average length of the growing period was 100 d for carrots, 88 d for celery, 66 d for Chinese cabbage (Pak choi), 45 d for Romaine and leaf lettuce, 60 d for crisphead lettuce, 110 d for onions, and 120 d for potato.

There were three replications and four to five P rates per site arranged in a randomized complete block design (Table 1). Sources of P were monoammonium phosphate (MAP) (11-52-0) or a mixture of dehydrated swine solids and monoammonium phosphate (3.2-15.5-0.8). It was assumed that manure N was 60% equivalent and manure K 100% equivalent compared to MAP similarly to solid manure (CRAAQ, 2003), but that manure P was equivalent to MAP. Nitrogen, K, and micronutrients were applied as recommended locally (CRAAQ, 2003). Fertilizers were broadcast before sowing or planting. Plots were four to six rows in width and 5 to 8 m long. Row spacing was 47 cm for carrots, lettuce, and onions, 55 for Chinese cabbage, 65 cm for celery, and 91 cm for potato. Other practices were those commonly used in the region. Yields were measured in two central rows or in the center of the bed over a length of 3 to 6 m (3–7 m^2 depending on the crop). Harvest date depended on the number of days to meet market requirement, the number of harvests during summer, and

Table 1. Phosphorus application rates at experimental sites.

Crop	2002–2003	2004–2005
	kg P ha ⁻¹	
Carrot	–	0, 13, 26, 52
Chinese cabbage	–	0, 15, 31, 61
Onion	0, 13, 26, 39	0, 13, 26, 52
Potato	0, 9, 17, 35	0, 13, 26, 52
Celery	0, 9, 17, 35, 52	0, 11, 22, 44
Lettuce	0, 9, 17, 35	0, 13, 26, 52

crop size category. The harvested portions of the plant in each plot were classified according to commercial standards and reported as commercial yield.

Soil Analysis

Soil surface materials covering a large spectrum of properties (22 peat samples collected by Vaillancourt et al. [1999] between the 45th and the 49th parallel in Quebec and 60 cultivated sapric materials collected by Duguet et al. [2006] between the 45th and the 46th parallel close to the fertilizer trials) were analyzed in duplicate. A second dataset comprised the soils collected at the fertilizer trial sites where five cores were composited in the root zone (0–30 cm) of each of three blocks before fertilization. Soils were air-dried to constant weight, and sieved to <2 mm. Soil pH was determined in 0.01 M CaCl₂ using a soil/solution volumetric ratio of 1:4. Organic C and N were quantified using the CNS-Leco2000 instrument. Loss on ignition (LOI) was quantified by burning the organic material for 16 h at 550°C. Total P was determined by colorimetry (Lavery, 1963) after dissolving the ashes from LOI with 0.1 M HCl. The P_{Bray1} was determined according to Bray and Kurtz (1945) and quantified by PES. A volume of 3 mL of organic soil material was scooped and extracted for soil P using 37.5 mL of distilled water to obtain the same soil/solution ratio as in the official Florida soil P test (Sanchez, 1990) (P_{Florida}). Soil P, Fe, and Al were extracted using the M-III method (Mehlich, 1984). Oxalate P (P_{OX}), Fe (Fe_{OX}), and Al (Al_{OX}) were extracted according to Ross and Wang (1993). Pyrophosphate Fe (Fe_{pyr}) and Al (Al_{pyr}) were extracted according to McKeague (1967). The acid ammonium oxalate method extracts non-crystalline and poorly crystalline Al and Fe (Fe_{II} and Fe_{III}) forms (Ross and Wang, 1993) that include organically bound (pyrophosphate-extractable) and oxy-hydroxide (oxalate-extractable minus pyrophosphate-extractable) forms of Al and Fe. The Florida, M-III, pyrophosphate, and oxalate extracts were quantified by PES.

The P_w was extracted in a 60:1 H₂O/soil ratio according to Sissinigh (1971) using NaCl across samples to clarify the suspension that was passed through a <0.45- μm filter. In contrast with mineral soils, where field bulk density (FBD) is generally similar to the reconstituted bulk density (RBD) as scooped weight (Khari et al., 1999), the FBD may be only 0.45 times the RBD after drying and sieving the peat (Erviö, 1969). The P_w value in air-dried and sieved materials must be corrected accordingly to be representative of field conditions. We found that for cultivated organic soils FBD was 0.753 times RBD after drying and sieving. For pristine peat materials of known von Post degree of humification (VPDH) (Vaillancourt et al., 1999), peat FBD depends on VPDH as follows (Silc and Stanek, 1977):

$$\text{FBD (g mL}^{-1}\text{)} = 0.0182\text{VPDH} + 0.0529, r^2 = 0.88 \quad [3]$$

The P_w values obtained from scooped soils was thus corrected for RBD as follows:

$$P_{w\text{-FBD}} = P_{w\text{-RBD}} \frac{\text{FBD}}{\text{RBD}} \quad [4]$$

We used $P_{w\text{-FBD}}$ in this study.

Statistical Analysis

The relationships between soil tests were determined by regression. The γ value in Eq. [2] was iterated until the r^2 value was maximized for the relationships between $\text{IPS}_{\text{M-III}}$ and either P_w or DPS_{OX} . The relative yield was computed by dividing

absolute yield in the control treatment by the highest yield among treatments with added P. The soil calibration study was conducted using the P response patterns of six crops. Type IV error may occur when interactions are examined (crop response by soil test combinations) although hypotheses require cell means to be analyzed or, conversely, cell means are examined when the hypotheses require that interactions be analyzed (Umesh et al., 1996). Soil fertility classification requires a minimum of two classes of crop response patterns defined graphically or by ANOVA (Nelson and Anderson, 1984). As a protection against type IV error, the six crops were compared in two groups of soil tests as delineated by a critical value of $\text{IPS}_{\text{M-III}}$ above which most crops no longer responded to added P as shown by relative yield close to 100%. The separation between the two soil test groups was varied by 0.1 $\text{IPS}_{\text{M-III}}$ units below and above an initial separation value, and F values were computed iteratively from ANOVA (SPSS vs. 13.1) for each $\text{IPS}_{\text{M-III}}$ separator to test the effects of the six crops and the two soil groups and their interaction (factorial design with unequal replications). If the interaction was not significant, type IV error was considered negligible and relative yields were averaged across crops as one random variable. A constraint on the initial $\text{IPS}_{\text{M-III}}$ separator was that all crops should be represented at least one time (one replication) in each soil group. Below 0.08 and above 0.17, there was no specimen of the onion crop, hence limiting the validity of $\text{IPS}_{\text{M-III}}$ separator to five crops outside that range.

RESULTS AND DISCUSSION

Soil Characteristics

In general, both soil datasets covered a similar spectrum of properties (Table 2). In the soil survey dataset, loss on ignition ranged between 292 and 991 g kg⁻¹, total carbon represented 0.57 of the loss on ignition, DPS_{OX} (0.458 ± 0.243) ranged between 0.033 and 1.035, and $\text{IPS}_{\text{M-III}}$ (0.138 ± 0.103) ranged between 0.003 and 0.419. The $\text{IPS}_{\text{M-III}}$ varied between 0.030 and 0.298 in the fertilizer trial dataset, so within the range of the soil survey dataset (Table 2). Hence, the soil survey dataset was representative of the fertilizer trial dataset.

The Fe content averaged 3.6 to 4.1 g Fe_{OX} kg⁻¹ and Al content averaged 1.4 to 1.7 g Al_{OX} kg⁻¹ across datasets (Table 2). In comparison with highest values of 9.8 g Fe_{OX} kg⁻¹ and 8.6 g Al_{OX} kg⁻¹ in Table 2, German bog (oligotrophic) peats contained 2.4 g total Fe kg⁻¹ (0.3–4.7) and 1.5 g total Al kg⁻¹ (0.2–3.6) and German fen (eutrophic) peats contained 17 g total Fe kg⁻¹ (1–26) and 10 g total Al kg⁻¹ (3–17) (Naucke et al., 1993). Efimov et al. (1996) reported values of 21 to 189 g Fe_{OX} kg⁻¹ in ferruginous bogs of Karelia (Russia) where the organic compounds were saturated with Fe, allowing the formation of mineral Fe compounds with high P sorption capacity. In Polish Histosols containing 1 to 81 g Fe_{OX} kg⁻¹, almost half of the Fe forms contributing to P fixation were organically bound (Wondrausch, 1969). In our study, pyrophosphate-extractable Al was close to oxalate-extractable Al, showing that Al was almost entirely associated (96%) with organic matter (Table 2). The pyrophosphate-extractable Fe accounted for 53% of oxalate-extractable Fe (Table 2), indicating the presence of other amorphous Fe forms than the ones related to organic matter.

Table 2. Range of soil properties in the survey and the field trial datasets.

Property†	Survey dataset (82 soils)				Field trial dataset (66 soils)			
	Mean	SD	Min	Max	Mean	SD	Min	Max
g kg ⁻¹ of soil								
Loss on ignition	740	169	292	991	771	133	158	928
C	421	99	147	580	446	75	97	524
N	18.8	5.2	7.2	34.2	20.1	5.2	6.1	38.8
mg kg ⁻¹ of soil								
Total P	778	599	59	2876	—	—	—	—
P _{OX}	708	548	24	2233	725	456	110	1951
g kg ⁻¹ of soil								
Al _{OX}	1.743	1.296	0.106	8.642	1.424	0.862	0.524	5.085
Fe _{OX}	4.091	2.326	0.207	9.397	3.579	2.242	0.799	9.826
Al _{pyro}	1.682	1.103	0.204	7.546	1.379	0.921	0.386	5.314
Fe _{pyro}	2.124	1.658	0.000	6.126	2.414	2.045	0.113	7.606
mg L ⁻¹ of scooped soil								
P _{M-III} ‡	140	118	2	531	170	107	16	475
Al _{M-III}	205	229	1	817	138	173	0	730
Fe _{M-III}	329	152	9	586	397	184	31	1153
P _w §	33.8	27.0	0.0	100.3	30.6	15.7	7.2	67.8
pH (CaCl ₂)	5.33	1.08	2.79	6.81	5.33	0.50	3.85	6.64
DPS _{OX} (α _m = 0.4)	0.438	0.243	0.033	1.035	—	—	—	—
IPSM-III (γ = 5)	0.115	0.085	0.003	0.419	0.126	0.068	0.030	0.298

† P_{OX}, Al_{OX}, Fe_{OX}, acid ammonium oxalate-extractable P, Al, and Fe, respectively; Al_{pyro}, Fe_{pyro}, pyrophosphate-extractable Al and Fe, respectively; P_{M-III}, Al_{M-III}, and Fe_{M-III}, Mehlich III-extractable P, Al, and Fe, respectively; P_w, water-extractable P (Sissin, 1971); DPS_{OX}, degree of P saturation; IPSM-III, [P/(Al+γFe)]_{M-III} ratio as an index of P saturation.

‡ Multiply by 1.8 to obtain a P index in kg ha⁻¹.

§ Water-extractable P (Sissin, 1971); corrected for field bulk density.

Soil Phosphorus Tests

The relationship between P_{M-III} and P_{Bray1} was found to be as follows in Quebec organic soils:

$$P_{M-III}(\text{mg L}^{-1}) = 1.56P_{Bray1}(\text{mg L}^{-1}), r^2 = 0.88 \quad [5]$$

In other studies, soils high in amorphous Fe and Al and organic C had slopes between 1.5 and 2.2 (Ping and Michaelson, 1986; Michaelson et al., 1987; Davenport et al., 1997). The slope of 1.56 in Eq. [5] differed markedly from slopes close to one reported for mineral soils of southern and Mid-Atlantic USA (Mehlich, 1984), Ultisols, Alfisols and Mollisols (Hanlon and Johnson, 1984; Wolf and Baker, 1985), Cryochrepts (Michaelson et al., 1987), Spodosols, and Inceptisols (Tran et al., 1990; Parent and Marchand, 2006). Indeed, strongly acidic extractants such as M-III were found to extract larger quantities of P compared to the Bray 1 extractant and to be more closely related to agronomic yield in acid volcanic ash soils containing 7.8 to 10.9 g Fe_{OX} kg⁻¹, 9.2 to 14.3 g Al_{OX} kg⁻¹, and 60 to 80 g C kg⁻¹ (Ping and Michaelson, 1986; Michaelson et al., 1987). The P appeared to be more easily extracted by the M-III compared to the Bray 1 extractant in Histosol materials high in C, Fe_{OX}, and Al_{OX} (Table 2) where Al_{pyr} and Fe_{pyr} forms may react with P.

Model Development

The γ coefficient was varied between 0 and 10 to maximize the relationship between IPSM-III on the one hand, and DPS_{OX} or P_w on the other (Fig. 1). The r² values tended to stabilize when γ increased above 3. We selected γ = 5 where r² reached its maximum value. The r² value was lower for the IPSM-III-P_w relationship compared to IPSM-III-DPS_{OX} because the variation in bulk density was more difficult to control in the P_w expression compared to the DPS_{OX} ratio.

Setting DPS_{OX} = 0.25 (Fig. 2), a critical environmental IPSM-III value of 0.05 was found for DPS_{OX} using α_m values of 0.4 (Breeuwsma et al., 1986). This critical IPSM-III value was validated as follows:

- (1) The relationship between IPSM-III (γ = 5) and P_w shows that for P_w = 9.7 mg P L⁻¹, IPSM-III = 0.05 (Fig. 3).
- (2) A North Carolina Wasda muck containing 1705 mg Al_{M-III} kg⁻¹ and 197 Fe_{M-III} kg⁻¹ showed a change point at 115 P_{M-III} kg⁻¹ (Bond et al., 2006). The environmental critical IPSM-III ratio was computed to be 0.05 as follows:

$$IPSM-III = \frac{115/31}{1705/27 + 5(197/56)} = 0.05 \quad [6]$$

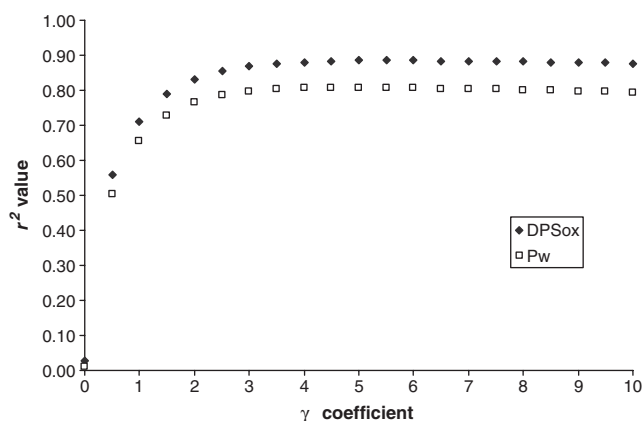


Fig. 1. The r² values for relationships between the [P/(Al+γFe)]_{M-III} ratio as an index of P saturation (IPSM-III) and the degree of P saturation (DPS_{OX}) (α_m = 0.4) or water-extractable P (P_w) by varying the γ coefficient in IPSM-III.

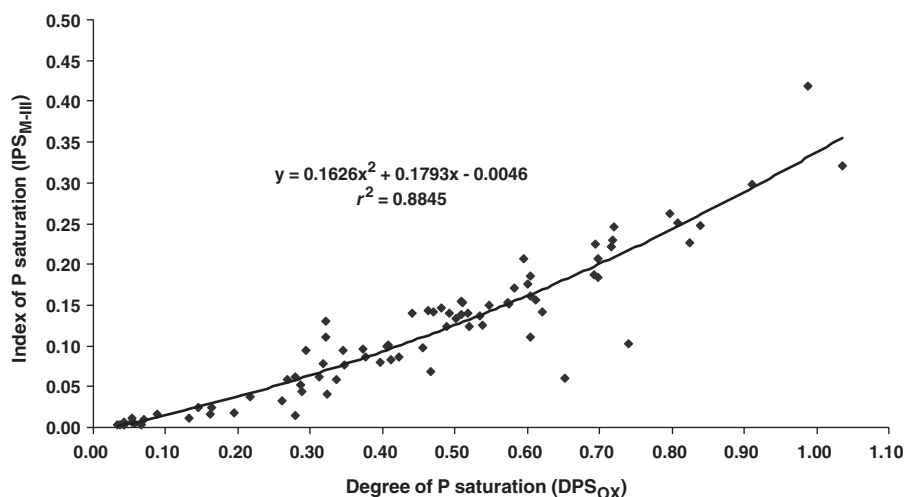


Fig. 2. Relationship between the $[P/(Al+\gamma Fe)]_{M-III}$ ratio as an index of P saturation (IPS_{M-III}) ($\gamma = 5$) and the degree of P saturation (DPS_{OX}) ($\alpha_m = 0.4$).

We thus selected 0.05 as critical environmental IPS_{M-III} value for Quebec Histosols. The IPS_{M-III} was more closely related to DPS_{OX} ($r^2 = 0.88$) compared to P_{M-III} ($r^2 = 0.74$), P_{Bray1} ($r^2 = 0.63$), and $P_{Florida}$ ($r^2 = 0.53$). Hence, compared to the Bray 1 and Florida extraction methods, the M-III method appeared to be more appropriate for the environmental assessment of inorganic P status. Among the 66 experimental sites, only five sites had IPS_{M-III} values below the environmental threshold of 0.05.

Soil Test Calibration

Carrots, potato, onion, and Chinese cabbage showed similar response patterns to added P (Group A: Fig. 4), while celery and lettuce seemingly formed another group (Group B: Fig. 5). The initial IPS_{M-III} agronomic threshold above which relative yield stabilized near 100% was approximately 0.16 in Group A (Fig. 4). There was no clear pattern in Group B (Fig. 5). Hence, the initial IPS_{M-III} value was fixed at 0.16 as in Fig. 4 to partition soil test values and was varied thereafter within the IPS_{M-III}

range of 0.08 to 0.19. There was no significant correlation at $P \leq 0.05$ between soil test and relative yield for each crop and soil group combinations (data not shown), indicating random effect of soil test within IPS_{M-III} group.

The ANOVA results showed no significant effect of the crop species ($P > 0.9$) or the crop by soil group interaction ($P > 0.3$). Hence, crop responses could be combined without making any significant type IV error. Only the soil group across crops had a significant effect that varied with the IPS_{M-III} separator (Fig. 6). The contrast between low-P and high-P soils was highest ($P < 0.05$) with IPS_{M-III} separators of 0.10, 0.13, and 0.15 (Fig. 6). Weighed relative yields accounting for the number of replications per crop averaged 98, 98, and 99% in the high-P soil group using the 0.10, 0.13 and 0.15 IPS_{M-III} separators, respectively. In high-P soils, it is generally required that relative yield average be above 98% (Bray, 1945) or even 99% (Melsted and Peck, 1977). The weighed yield average was 92 to 94% at low-P sites across separators, hence below the critical value of 95% for relative yields separating highly responsive

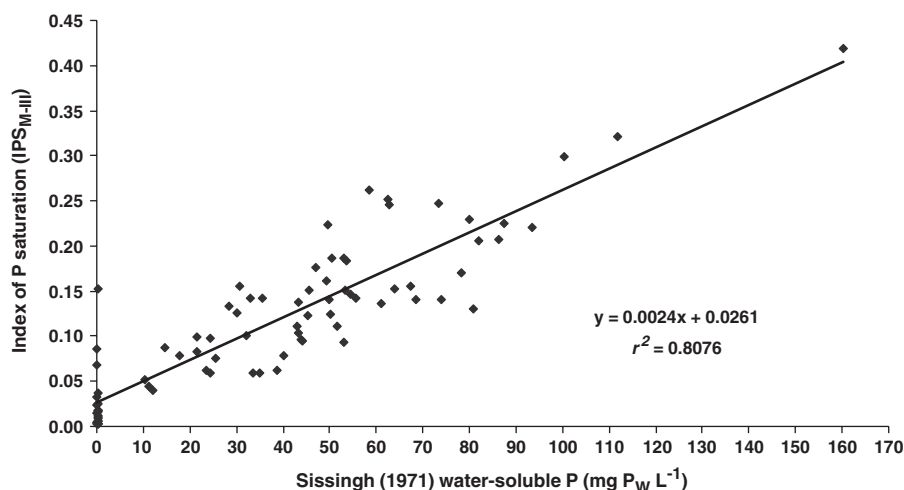


Fig. 3. Relationship between the $[P/(Al+\gamma Fe)]_{M-III}$ ratio as an index of P saturation (IPS_{M-III}) ($\gamma = 5$) and water-extractable P (P_W).

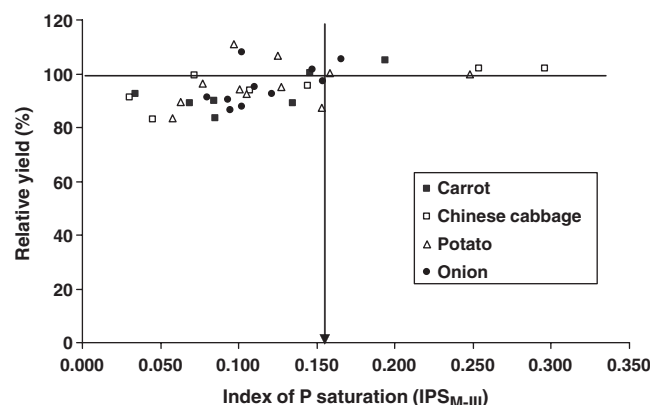


Fig. 4. Relationship between relative yield and the $[P/(Al+\gamma Fe)]_{M-III}$ ratio as an index of P saturation (IPS_{M-III}) ($\gamma = 5$) across Group A crops.

from less responsive crops using nonlinear models (Black, 1993). Hence, the 0.10, 0.13, and 0.15 IPS_{M-III} values appeared valuable separators between low- and high-P organic soils.

Obviously, the environmental threshold was lower than the agronomic thresholds in Histosols. In contrast, the environmental threshold was higher than the agronomic threshold for potato (*Solanum tuberosum* L.) (Khiari et al., 2000), cranberry (*Vaccinium macrocarpon* Ait.) (Parent and Marchand, 2006), and corn (*Zea Mays* L.) in mineral soils (Pellerin et al., 2006b). As a result, the vegetable production on Histosols poses a greater environmental risk than crop productions on mineral soils. The poor water quality of Norton Creek confirms this (Simoneau, 1996). Above IPS_{M-III} of 0.05, the P balance (added P minus P removal by the harvested portion of the crop) should thus be negative to minimize the risk of P contamination of surface and groundwater. Using 0.05 and either 0.10, 0.13, or 0.15 as IPS_{M-III} separators for establishing agri-environmental soil fertility classes, phosphorus fertilization concepts must be developed to minimize externalities of the P fertilization of vegetable crops grown on Histosols.

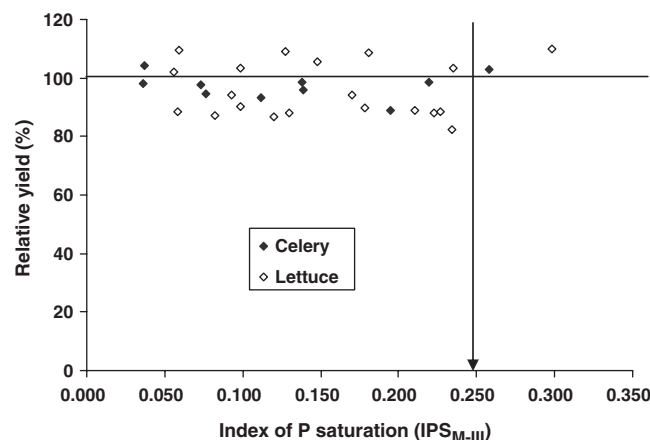


Fig. 5. Relationship between relative yield and the $[P/(Al+\gamma Fe)]_{M-III}$ ratio as an index of P saturation (IPS_{M-III}) ($\gamma = 5$) across Group B crops.

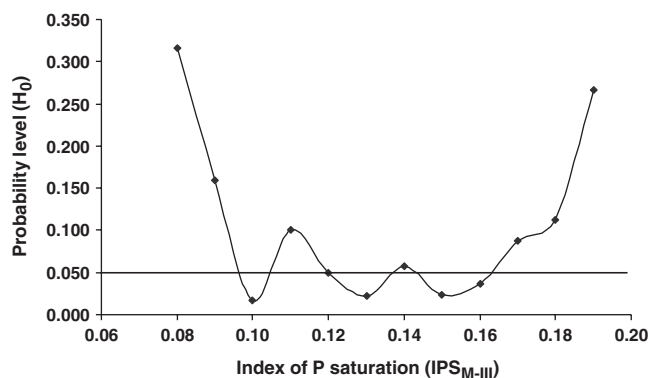


Fig. 6. Significance (α level for rejecting H_0) of the partition between two soil groups below or above the $[P/(Al+\gamma Fe)]_{M-III}$ ratio as an index of P saturation (IPS_{M-III}) separator on the x axis.

CONCLUSIONS

The M-III method, recognized to be more appropriate than the Bray 1 method for soils high in C and oxyhydroxides of Al and Fe, was evaluated in Histosols. A general expression of the degree of P saturation for organic soils using the M-III method (IPS_{M-III}) was proposed as $[P/(Al+\gamma Fe)]_{M-III}$, where γ was set at 5 to account for the role of Fe forms in P retention in organic soils. The IPS_{M-III} ($\gamma = 5$) was closely related to the P_w and DPS_{OX} ($\alpha_m = 0.4$). The critical thresholds of 0.25 as DPS_{OX} and 9.7 mg $P_w L^{-1}$ suggested in the literature corresponded to the IPS_{M-III} value of 0.05. Above the IPS_{M-III} of 0.05, the P balance (added P minus P removal by the harvested portion of the crop) should be negative to minimize the risk of P contamination of surface and groundwater. The environmental threshold was found to be lower than agronomic thresholds (0.10, 0.13 and 0.15) across vegetables, hence confirming the higher environmental risk of adding P to Histosols compared to mineral soils. The 0.05 as well as 0.10, 0.13, or 0.15 IPS_{M-III} separators will be useful benchmarks for implementing beneficial P management practices minimizing the externalities of P fertilization of vegetable crops grown on Histosols.

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