

DIVISION S-8—NUTRIENT MANAGEMENT & SOIL & PLANT ANALYSIS

Anion Exchange and Mehlich-III Phosphorus in Humaquepts Varying in Clay Content

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ABSTRACT

Soil-test P is not only used for fertilizer recommendations but also as a component to predict risk of P transfer from soils to surface waters. The changes in soil-test P following P application are often related to soil texture. This study assessed the changes in anion-exchange membrane P (AEM-P) and Mehlich-III extractable P (M3P) in Humaquepts varying in clay content. Five soils from loamy sand to “heavy” clay received 0 (P0), 10 (P10), 20 (P20), or 40 (P40) mg P kg⁻¹ per each simulated growth season were successively cropped with barley (*Hordeum vulgare* L.) and soybean (*Glycine max* L. Merr.) in a growth chamber experiment. There were clay content mineral fertilizer P (MFP) interactive effects on soil AEM-P, M3P contents and plant P uptake. The AEM-P paralleled clay content and MFP rate. The average increase in M3P at P10 and P20 over P0 was smaller on clayey than on coarse-textured soils. The converse trend was true at P40 over P10 and P20. The increase in M3P per unit MFP addition in excess of plant uptake decreased linearly with the increase in clay at P10 and P20 but not at P40. There was a quadratic plateau relationship between AEM-P and M3P contents with a turning point at 4.2 µg AEM-P cm⁻² or 93.0 mg M3P kg⁻¹. Plant P uptake was more closely related to AEM-P than M3P in all soils, suggesting AEM-P is a more reliable indicator of labile P than M3P in Humaquepts for the tested crops, particularly in fine-textured soils. Clay content has a large influence on changes in AEM-P and M3P following MFP additions to Humaquepts.

FORECASTING CHANGES IN SOIL-TEST P is a requirement of regulations on the agronomic use of fertilizer P in agricultural soils. A single value of change in soil-test P per unit fertilizer P added is being used to manage P inputs on Quebec soils (Ministry of Environment of Quebec, 1999). However, soil texture is known to have a large influence on soil retention-desorption capacities (Huffman et al., 1996; Leclerc et al., 2001). Soils with high clay contents have normally larger soil P buffering capacities and lower amounts of extractable P than coarse-textured ones (Kamprath and Watson, 1980). The increase in extractable P per unit of fertilizer P added was found to be much smaller on the fine-textured than the coarse-textured tropical soils (Johnston et al., 1991; Cox, 1994). The prediction of changes in soil-test P is required in the new regulations for reducing

non-point pollution in Quebec (Ministry of Environment of Quebec, 1999). Water-soluble P content in soils was shown to be closely related to P concentration in overland and subsurface waters (Simard et al., 1998; McDowell and Sharpley, 2001). Drainage water from coarse-textured and fine-textured Aquepts had a larger P concentration than from medium-textured soils (Beauchemin et al., 1998). The influence of soil texture on changes in soil-test P must thus be precisely determined to develop agro-environmental guidelines for better control of P use in agricultural soils.

The M3P is currently proposed as a main criterion to recommend fertilizer P in Quebec (Conseil des Productions Végétales du Québec, 1996). Mehlich-III P was chosen because of the close relationship between M3P and plant P uptake (Tran and Giroux, 1990; Simard et al., 1991) and of its multi-element extraction reducing the cost of soil testing. The ability of this method in predicting the amount of fertilizer P needed to achieve the maximum crop yield is however often limited, since it estimates only a small portion of labile P and ignores the slow release of sorbed P (Steffens, 1994) and soil organic P mineralization (Kamprath and Watson, 1980; Tiessen et al., 1994). As a growing plant continuously removes phosphate ions from soil solution, evaluating the soil capacity to maintain solution P from all labile pools is important.

Anion exchange membranes (AEMs) were proposed as an alternative to chemical extraction to assess the availability of soil P. The AEMs simulate the action of plant roots in continuously absorbing nutrients from solution (Yang et al., 1991), and estimate both solution concentration of nutrients and their rates of diffusion in soils (Abrams and Jarrell, 1992). Accordingly, AEMs reflect changes in soil solution concentration of the nutrients, which are sensitive to the on-site biotic and abiotic factors of soils (Cooperband and Logan, 1994). Previous reports have shown that this approach has potential to be a more accurate indicator of soil nutrient availability than chemical extraction procedures (Schoenau and Wang, 1991; Qian et al., 1992; Ziadi et al., 2001). The influence of clay content on the effectiveness of this desorption method is however unknown.

The objectives of this study were, therefore, (i) to examine the effects of clay content on the changes in

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Abbreviations: AEM, anion-exchange membrane; AEM-P, anion-exchange membrane P; DSPS, degree of soil P saturation; M3P, Mehlich-III extractable P; MFP, mineral fertilizer P; subscript ox, ammonium-oxalate extractable; P0, 0 mg P kg⁻¹ treatment; P10, 10 mg P kg⁻¹ treatment; P20, 20 mg P kg⁻¹ treatment; P40, 40 mg P kg⁻¹ treatment.

AEM-P and M3P following fertilizer application in soils, and (ii) to assess the reliabilities of AEM-P and M3P as criteria to predict plant-available P on Humaquepts varying in clay content.

MATERIALS AND METHODS

Soil Materials and Characterization

Five agricultural Humaquepts representing a gradient in clay content and a difference in parent materials (Nolin et al., 1991), were selected from the Ap horizon (0–20 cm) of the Fleury (sandy over Loamy, mixed, mesic, Typic Humaquept), Aston (sandy over clayey, mixed, mesic, Typic Humaquept), Saint-Aimé (coarse-silt, mixed, mesic, Typic Humaquept), Providence (fine clayey, mixed, mesic, Aeric Humaquept), and St-Urbain (very fine clayey, mixed, mesic, Typic Humaquept) series in the St. Lawrence lowlands in the Province of Québec, Canada. The samples were sieved through a 6-mm sieve and stored at 4°C until use for the pot experiment. Soil pH was measured in distilled water with a soil/solution ratio of 1:2. Particle-size separation was achieved by the hydrometer method (Sheldrick and Wang, 1993). Total C and N were determined by dry combustion (CNS-1000 Analyzer, Leco Corp., St Joseph, MI). The M3P was measured as described by Mehlich (1984). Ammonium-oxalate-extractable Al (Al_{ox}), Fe (Fe_{ox}), and P (P_{ox}) were determined according to Ross and Wang (1993). The degree of soil P saturation (DSPS) was calculated as the $P_{ox}/(Al_{ox} + Fe_{ox})$ molar ratio (van der Zee et al., 1988). Total soil P was determined by digestion in an autoclave (103.4 kPa, 121°C for 1.5 h) with 0.9 M H_2SO_4 and $K_2S_2O_8$ (Environmental Protection Agency, 1971). The selected physical and chemical properties of the five soils are shown in Table 1.

Outline of Pot Experiment

Amounts of 0 (P0), 10 (P10), 20 (P20), and 40 (P40) mg P as $NH_4H_2PO_4$ per kilogram of soil per growth phase (2-mo crop growth period from seeding to cutting) were mixed with soils and placed in 2-L pots. The pots were distributed according to a split plot design in four replicates with soil texture as the main factor and fertilizer P rate as the sub factor, in an environment-controlled chamber (6 by 15 m). The split plot design was used to probe into the fate of MFP on each tested soil. Each pot received 150 mg of N as NH_4NO_3 or $NH_4H_2PO_4$, 150 mg of K as KCl, 25 mg of Mg as $MgSO_4 \cdot 7H_2O$,

1 mg of Cu as $CuSO_4 \cdot 5H_2O$, 1 mg of Zn as $ZnSO_4 \cdot 7H_2O$, 1 mg of Mn as $MnSO_4 \cdot 2H_2O$, and 0.1 mg of Mo as $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ (Simard et al., 1991). Throughout the experiment, soil moisture was adjusted daily in the morning to 85% of field capacity (–33 kPa) by weighing. The temperature was controlled at $22 \pm 3^\circ C$, and artificial lighting was maintained daily for 16 h at $150 W m^{-2}$. Spring barley (*Hordeum vulgare* L. cv. Chapais) and soybean (*Glycine max* L. cv. Maple Glen) were grown successfully across two rotation cycles (barley–soybean in two turns) as test plants.

Twelve barley seeds were planted in each pot and the seedlings were thinned to six plants 1 wk after emergence. One AEM strip per pot was inserted 2 d after nutrient addition. The resin strips were removed after a 2-wk contact for the extraction of AEM-sorbed P. The plants were harvested by cutting at the soil surface after 2 mo of growth. Thereafter, a 2-wk freeze–thaw phase was applied to soils to simulate field conditions. All pots were first stored at $-10^\circ C$ for 1 wk. The pots were then taken out to thaw for 1 wk in a glasshouse. After this step, the soils were removed from the pots, separated from root collars and visible roots, mixed, sampled for further M3P analysis, and returned to the pots. Root collars and visible roots could not be decomposed during the 2-wk freeze–thaw phase. The removal of these plant tissues was assumed to have little influence on inorganic P contents in soils.

In the soybean growth phase, eight seeds were planted in each pot and thinned to three plants 1 wk after emergence. The AEMs test, P and K fertilizers, and micronutrient (Mg, Cu, Zn, Mn, and Mo) additions, freeze–thaw, and daily management in the chamber were similar to that of the barley growth phase. The basal N application was reduced to 100 mg of N per pot as NH_4NO_3 to account for the soybean N fixation capacity. Plant tissues were dried at $65^\circ C$ for 48 h, and weighed. A wet digestion with concentrated (18.0 M) H_2SO_4 and 30% (v/v) H_2O_2 were used for determination of P content in plant tissues (Richards, 1993). Phosphorus concentrations in digests were determined by colorimetry according to Tandon et al. (1968). The plant P uptake was estimated as the product of dry matter yield and tissue P concentration.

Anion-Exchange Membranes

The AEMs used in this study (type 204-U-385, Ionics Inc., Watertown, MA), are strong base quaternary ammonium anion exchangers. The package sheet was cut into 2.5 by 5.0 cm strips to allow the insertion of the strips into 30-mL centrifuge tubes used for elution (Ziadi et al., 1999). The membranes

Table 1. Average values ($n = 4$) of selected physical and chemical properties of five Humaquepts.

Property	Fleury†	Aston	Saint-Aimé	Providence	St-Urbain
Textural class	Loamy sand (LS)	Loam (L)	Clay loam (CL)	Clay (C)	“heavy” clay (HC)
Parent material	Fluvial sand	Fluvial	Lacustrine	Alluvial clay	Marine clay
pH	5.9 a	5.7 a	5.6 a	6.0 a	6.2 a
Clay, g kg ⁻¹	101 e	193 d	275 c	400 b	656 a
Silt, g kg ⁻¹	152 c	351 b	325 b	447 a	210 c
Sand, g kg ⁻¹	747 a	456 b	400 c	203 d	134 e
Bulk density, g cm ⁻³	1.12 c	1.16 bc	1.20 b	1.26 a	1.28 a
C, g kg ⁻¹	10.4 d	9.5 e	17.4 c	19.6 b	29.0 a
N, g kg ⁻¹	0.9 e	0.7 d	1.4 c	1.5 b	2.1 a
Mehlich-III extractable P, mg kg ⁻¹	57.3 c	49.2 d	65.2 b	57.4 c	71.5 a
Ammonium-oxalate extractable					
P_{ox} , mmol kg ⁻¹	6.2 d	7.2 c	7.0 c	14.4 b	22.3 a
Al_{ox} , mmol kg ⁻¹	65.1 d	64.4 d	72.8 c	81.8 b	120.9 a
Fe_{ox} , mmol kg ⁻¹	26.9 e	37.6 d	49.7 c	115.7 b	181.2 a
$Al_{ox} + Fe_{ox}$, mmol kg ⁻¹	92.0 d	102.0 d	122.5 c	197.5 b	302.1 a
DSPS, mmol mmol ⁻¹ †	0.067 a	0.071 a	0.057 b	0.073 a	0.074 a
Total P, mg kg ⁻¹	510 e	594 d	669 c	792 b	1086 a

† Within same row, means followed by the same letter are not statistically different at $P \leq 0.05$ according to Tukey HSD test.

‡ DSPS, degree of soil P saturation = $P_{ox}/(Al_{ox} + Fe_{ox})$ (van der Zee et al., 1988).

were first cleaned with 0.5 M HCl and were converted to the Cl⁻ form by immersion in 1 M NaCl. The membranes were then thoroughly rinsed and kept in distilled water until use. The top end of the strips was perforated and a fishing line was attached. The AEMs were inserted near the soil surface (2–7 cm) through a slice opened with a small shovel. Once excavated from soil, the membranes were rinsed with deionized water to remove adhering soil particles, and immediately placed into 300-mL Nalgene tubes containing 25 mL of 1 M NaCl. The elution was performed by shaking the tubes for 2 h in an end-over-end shaker. After elution, the membranes were removed from the tubes, rinsed and recycled (cleaning and saturation) for later use. The concentration of P in the eluent was determined colorimetrically by the molybdate-ascorbic acid method (Murphy and Riley, 1962), and the data were expressed as AEM-sorbed P (AEM-P, μg cm⁻² AEM area).

Data Analysis

The normality of the distribution of each variable was tested and a log-transformation was applied when necessary to improve normality. The Tukey HSD test was used for mean separation of soil physical and chemical properties. All variables were analyzed with a split-plot analysis of variance (AN-OVA) design to determine the significance of treatment effects. The ANOVA was performed separately for each phase of rotation. The sum of squares for treatments was partitioned into orthogonal contrasts to evaluate the significance of differences between mean values. The REG and NLIN procedures were used for linear regression and quadratic plateau analysis, respectively. All statistical analyses were conducted using the SAS software (Statistical Analysis System Institute, 1990).

RESULTS AND DISCUSSION

Characteristics of Tested Soils and Initial Phosphorus Status

The five soils were slightly acidic and their clay contents ranged from 101 to 656 g kg⁻¹ (Table 1). Their initial M3P contents ranged from medium (40–55 mg M3P kg⁻¹) to adequate (56–70 mg M3P kg⁻¹) for barley and soybeans (Conseil des Productions Végétales du

Québec, 1996). The fine-textured soils (clay and heavy clay) had larger P_{ox} content and soil P sorption capacity as the sum of Al_{ox} and Fe_{ox}, than the coarse-textured ones (loamy sand, loam and clay loam). The sum of Al_{ox} and Fe_{ox} was proportional to clay content ($r = 0.99, P < 0.001$) in tested soils. This agrees with Lins and Cox (1989) and Beauchemin and Simard (2000), who previously reported strongly positive relationships between clay content and P sorption capacity in comparable soils. Total soil C, N, and P contents were also strongly related to soil clay content ($r \geq 0.94, P < 0.001$).

Plant Phosphorus Uptake

The relative effectiveness of fertilizer P can be measured by increased crop yield or P uptake. The latter is more directly related to increased P content in crops because of P fertilization (Ivarsson, 1990). There were interactions on plant P uptake between soil texture and MFP rate (Table 2). At MFP ≤ 20 mg kg⁻¹ phase⁻¹, the average increase in plant P uptake in clayey soils (clay and heavy clay) over control (P0) was larger than in loamy sand and loam soils. Whereas the converse trend was true when MFP was increased from 20 to 40 mg kg⁻¹ phase⁻¹ (Fig. 1a). The distinction in plant P uptake following MFP addition to soils suggests that it may be necessary to group Humaquepts by textural classes when evaluating the effectiveness of MFP applied to crops.

Phosphorus uptake by barley from control soils was lowest in the loamy sand. This is attributable to its relatively lower native P supply as compared with the finer-textured soils (Table 1). The Mehlich-III solution extracts a smaller portion of available P on clayey soils than that on the coarser-textured soils (Kamprath and Watson, 1980). Therefore, the differences in native available P in tested soils are even more than that indicated by the M3P values in Table 1. The P uptake by plant on a fine-textured soil may reach a plateau quicker than on a coarse-textured soil, because of its higher soil

Table 2. Significance levels of effects of soil texture and mineral-fertilizer P (MFP) addition on amounts of anion-exchange membrane P (AEM-P), Mehlich-III extractable P (M3P), and plant P uptake.

Source of variation	Phase I (barley)			Phase II (soybean)			Phase III (barley)			Phase IV (soybean)		
	AEM-P	M3P	P uptake	AEM-P	M3P	P uptake	AEM-P	M3P	P uptake	AEM-P	M3P	P uptake
Soil texture (ST)‡	**	***	***	**	***	***	***	**	***	**	**	***
LS vs. (L + CL)	**	*	***	***	NS†	NS	***	*	***	***	*	NS
(LS + L + CL) vs. (C + HC)	***	*	***	**	***	**	*	NS	***	NS	NS	***
Mineral fertilizer P (MFP)§	***	***	***	***	***	***	***	***	***	***	***	***
P0 vs. (P10 + P20)	***	***	***	***	***	***	***	***	***	***	***	***
(P10 + P20) vs. P40	***	**	***	**	***	***	***	***	***	***	***	***
P20 vs. P40	***	***	***	***	***	***	***	***	***	***	***	***
ST × MFP	NS	*	**	NS	*	**	*	**	**	*	*	*
LS vs. (L + CL) * P0 vs. (P10 + P20)	NS	*	***	NS	**	NS	NS	***	*	NS	**	NS
LS vs. (L + CL) * (P10+P20) vs. P40	NS	NS	NS	*	NS	NS	**	NS	NS	NS	NS	NS
LS vs. (L + CL) * P20 vs. P40	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
(LS + L + CL) vs. (C + HC)* P0 vs. (P10 + P20)	*	*	*	NS	*	***	*	**	**	**	*	*
(LS + L + CL) vs. (C + HC)* (P10 + P20) vs. P40	NS	NS	***	NS	NS	NS	**	NS	**	NS	NS	NS
(LS + L+CL) vs. (C + HC) * P20 vs. P40	NS	NS	***	NS	NS	**	*	**	***	**	*	*

* Significant at P ≤ 0.05.

** Significant at P ≤ 0.01.

*** Significant at P ≤ 0.001.

† NS not significant.

‡ LS, L, CL, C and HC refer to loamy sand, loam, clay loam, clay and heavy clay soil, respectively.

§ P0, P10, P20 and P40 refer to P addition at rate of 0, 10, 20, and 40 mg P kg⁻¹ phase⁻¹, respectively.

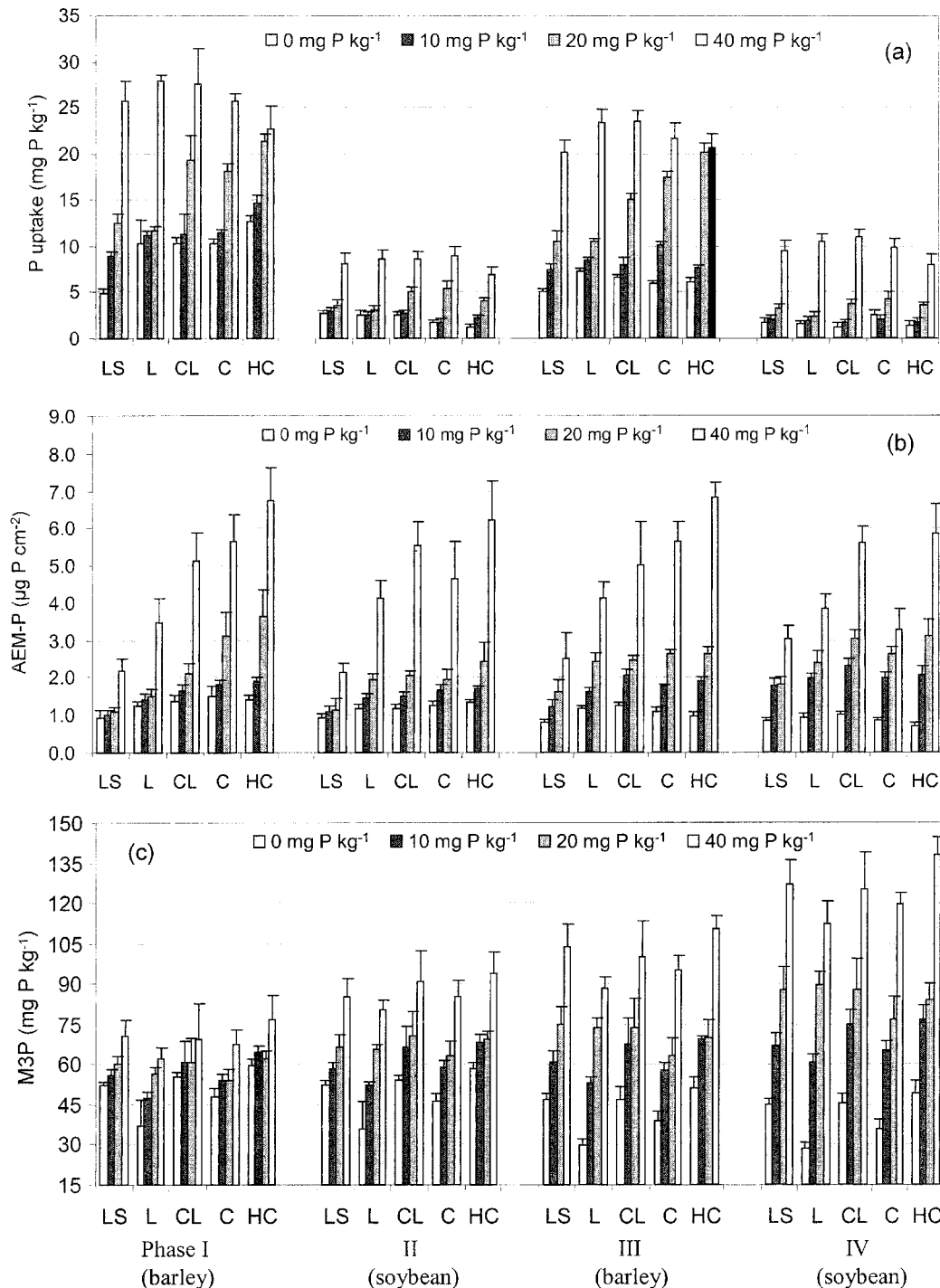


Fig. 1. Amounts of (a) plant P uptake, (b) anion-exchange membrane P (AEM-P), and (c) Mehlich-III extractable P (M3P) as influenced by soil texture and mineral fertilizer P (MFP) addition (bars are standard errors).

available P. This reflects that the heavy clay soil in this study had a least change in plant P uptake than other soils, while increasing MFP from 20 to 40 mg kg⁻¹ phase⁻¹ (Fig. 1a). Across tested soils, plant P uptake was more closely related to MFP rate ($r = 0.96$, $P < 0.001$) than to clay content ($r = 0.57$, $P < 0.05$), confirming the results of Ivarsson (1990).

Anion-Exchange Membrane Phosphorus

The amount of AEM-P in soils was significantly influenced by soil texture and MFP rate during the first

barley–soybean rotation (Table 2). Averaged across four MFP rates, the amount of AEM-P in fine-textured soils was 2.1 times larger during the barley growth phase and 1.5 times larger during the soybean growth phase compared with coarse-textured soils (Fig. 1b). Soil AEM-P was however comparable between the two clayey (clay and heavy clay) and also between the two loamy soils (loam and clay loam) at MFP ≤ 20 mg kg⁻¹ phase⁻¹.

There were weak but significant interactions between soil texture and MFP rate on AEM-P during the second

barley–soybean rotation (Table 2). The interactions stemmed mainly from the distinct responses of soil groups to added MFP. At P10 and P20, the average increase in AEM-P over P0 ($0.78 \mu\text{g cm}^{-2}$) for the two clayey soils was much larger than for the three coarse-textured soils ($0.41 \mu\text{g cm}^{-2}$). The average increase in AEM-P at P40 over P10 and P20 in the two loamy soils ($2.08 \mu\text{g cm}^{-2}$) was also significantly larger than in the loamy sand ($0.81 \mu\text{g cm}^{-2}$), but was lower than in clayey soils ($4.01 \mu\text{g cm}^{-2}$), when soils were cropped to barley for the second time (Phase III). This difference disappeared once soils were cropped to soybeans (Phase IV). The specific increase in AEM-P between the coarse-textured and fine-textured soils once again emphasized the importance of clay content in affecting the residual effects of MFP in the investigated soils. The AEM-P is a measure of soil soluble and readily desorbable P (Cooperband et al., 1999). The observation from the present study is in agreement with Simard et al. (1991) who reported that accounting for clay content significantly improved the relationship between water-soluble P and plant-available P. Clayey soils presented a larger increase in AEM-P than coarse-textured soils when MFP increased from 20 to $40 \text{ mg kg}^{-1} \text{ phase}^{-1}$ (Fig. 1b). This change in AEM-P results from lower plant P uptake, which leaves more P in soil solution.

The amount of AEM-P at P40 was much higher than that at lower MFP rates, since the added MFP was largely in excess of plant removal and some of MFP was left in the soil solution (Fig. 1b). The amount of P desorbed by AEMs from soils increased proportionally to MFP rate and to clay content ($r \geq 0.78$, $P < 0.01$). According to Kamprath and Watson (1980), clayey soils normally have larger soil P buffering capacities and lower amounts of soluble P than coarse-textured soils. However, the highest AEM-P value was found in the heavy clay in spite of the largest P sorption capacity ($\text{Al}_{\text{ox}} + \text{Fe}_{\text{ox}}$) of all soils tested in this study (Table 1). A recent investigation on the P status of 27 intensively cropped soils of St-Lawrence Lowlands (mostly Humaquepts) varying in clay content also indicated that highest water-soluble P values in A horizon were associated with clayey soils (Beauchemin and Simard, 2000). The AEM-P is sensitive to diffusion. Diffusion of P in soils is governed by on-site biotic and abiotic processes (Frossard et al., 2000). Higher C contents and relatively higher microbial activities in clayey soils (Bissonnette et al., 2001; Zheng et al., 2001) may have contributed to a higher diffusion rate in clayey compared with coarse-textured soils (Morel et al., 2000).

At P40, clay loam and heavy clay soils were comparable with respect to AEM-P values when soils were under soybeans (Phase II and IV) but not under barley (phases I and III). This suggests that plant species influence soil soluble and readily desorbable P pools by their specific P uptake characteristics and root activities. Loneragan (1978) indicated that crop species differently contribute to plant-available P in soils from their three distinct root attributes: (i) the physiological ability to absorb P from soil solution; (ii) metabolic activity resulting in solubilization of sorbed P; and (iii) the ability of the root system to explore the soil mass. The AEM-P content at P40 in

clay is much lower than the comparable values for clay loam and heavy clay when soils were under soybeans. The actual reason for this is not clear, but it might be related to its lower native available P compared with clay loam and heavy clay soils (Table 1).

Mehlich-III Extractable Phosphorus

There were also interactions between soil texture and MFP rate on M3P in all cropping phases (Table 2). Interactions were, however, more consistent than that observed for plant P uptake. The average increase in M3P content at P20 over P0 was, throughout the experiment, about 1.5 times larger in the three coarse-textured soils than in the two fine-textured soils (Fig. 1c). This trend did not agree with the changes in AEM-P at P20 over control soils (Fig. 1b). This discrepancy may stem from differences in the mechanism of soil P desorption between methods and also in the measuring time. Since M3P was measured once at the end of each growth phase, it gives only a glimpse at soil P, without providing any estimate of the diffusion and mineralization components of bioavailability (Abrams and Jarrell, 1992). The AEM-P measurement was made at the end of the first 2 wk of the experiment. It is a measure of soil-solution P and of readily desorbable P over a 2-wk period (Cooperband et al., 1999). Soil-solution P represents the balance between opposite processes: those depleting soil solution P such as plant uptake, soil P immobilization by microbial biomass and P precipitation in the soil, and those replenishing soil solution including mineralization and desorption from the soil solid phase to soil solution (Frossard et al., 2000). The AEMs placed in situ integrated the net effect of these processes on soil P through the whole contact period rather than a single point contact such as in most soil-test procedures (Cooperband and Logan, 1994; Ziadi et al., 2001). The AEM-P therefore reflects the P transfer rate between soil constituents and soil solution (Morel et al., 2000), which is cited as a governing factor for P bioavailability in soils (Yang et al., 1991; Frossard et al., 2000).

At the second barley–soybean rotation, increases in M3P at P40 over P20 were higher in clayey ($31.1\text{--}48.2 \text{ mg kg}^{-1}$) than in coarse-textured soils ($23.5\text{--}32.9 \text{ mg kg}^{-1}$, Fig. 1c). This is probably because of a larger increase in plant P uptake at P40 over P20 in coarse-textured soils compared with fine-textured soils (Fig. 1a). It is also partly related to pathways of P transformations in soils. When fertilizer is added in excess of plant uptake, labile inorganic P (P_i) may be partly immobilized as stable organic P (P_o), a pool that is not soluble in the Mehlich-III solution (Zheng et al., 2002).

The loam had a significantly lower initial M3P content and relatively larger increase in M3P following MFP addition than fine-textured soils (Fig. 1c). This is attributable to smaller P buffer capacity as indicated by a smaller value of ($\text{Fe}_{\text{ox}} + \text{Al}_{\text{ox}}$) (Table 1). The M3P increased proportionately to MFP across soils. The amount of M3P increased with time as more P was added than exported by harvested portions of succeeding crops.

The change in M3P per unit of net P surplus (added

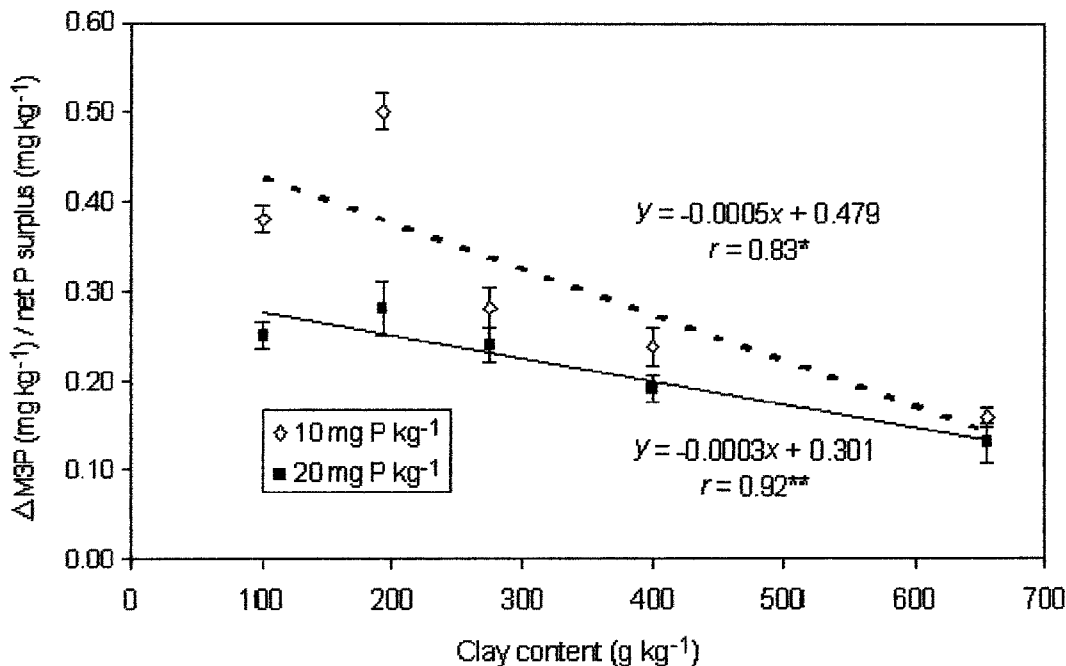


Fig. 2. Relationships between change in Mehlich-III extractable P (M3P) per unit of net P surplus and clay content at three mineral fertilizer P (MFP) rates (*, **, significant at $P < 0.05$ and $P < 0.01$, respectively).

P minus plant P removal across experiment) is a more meaningful indicator than the amount of M3P in soils to evaluate residual effects of fertilizer P applications (Cox, 1994). This indicator, as computed by difference in M3P values between pretest and posttest, divided by the total P applied at a rate exceeding P removal, was related to clay content (Fig. 2). The fitted function decreased linearly when MFP was applied at rates of 10 and 20 mg P kg⁻¹ phase⁻¹. Previous reports also showed that, at low to medium rates of P addition, soil test P (M3P, Bray-P) increased faster in coarse-textured soils than in fine-textured soils (Johnston et al., 1991; Cox, 1994). However, the change in M3P per unit P surplus at the rate of 40 mg kg⁻¹ phase⁻¹ did not depend on clay content (data not shown). This is probably because of higher soil P saturation masking the effects of soil texture on soil test P.

Relationships between Plant P Uptake and AEM-P or M3P

Plant P uptake was more closely related to AEM-P than M3P across tested soils. The relationship between P uptake and M3P was not significant for heavy clay soil (Fig. 3). This is probably related to the relative inability of Mehlich-III extraction to desorb the plant-available soil P (Morel et al., 2000). The M3P method, because of the low pH of extraction, may dissolve a significant proportion of unavailable Al and Ca bound P, but ignores the mineralization of organic P (Yang et al., 1991; Fardeau et al., 1988). The relationships between plant P uptake and AEM-P or M3P from the present study, suggest that AEM-P is a more reliable indicator of labile P on Humaquepts, particularly for fine-textured soils. This agrees with previous reports showing that AEM-P was closely related to soil solution

P and plant P uptake under controlled conditions (Sagar et al., 1990; Abrams and Jarrell, 1992). Compared with chemical extracting agents, AEM has been reported to be more closely related to forage P uptake in fine-textured Cryaquepts of Abitibi-Temiscaming (Ziadi et al., 2001), and to the potato (*Solanum tuberosum* L.) response to P fertilizer in coarse-textured soils (Simard et al., 1999). Previous studies have indicated that P availability to plants from soils receiving long-term fertilizer additions was assessed more accurately by release rates from repeated desorption studies than by a single chemical extraction (Qian et al., 1992; Steffens, 1994). This is also the case for extensively managed fine-textured Cryaquepts (Ziadi et al., 2001). Previous reports plus the observation from the present study suggest that AEMs are reliable in assessing soil nutrient availability.

A quadratic plateau relationship was found between soil M3P and AEM-P with a turning point at about 4.2 μg AEM-P mg⁻¹ and 93.0 mg M3P kg⁻¹ (Fig. 4). This indicated that, above those threshold values, desorption of soil P to AEMs was not limited by the size of the quantity factor such as the M3P pool, but rather by physical and biological factors. The apparent plateau in clayey soils indicated a disagreement between M3P and AEM-P as indicators of labile P in fine-textured soils. The Mehlich-III solution has been shown to underestimate plant-available P in some Quebec soils rich in clay (Tran et al., 1990; Simard et al., 1991). The relationship between M3P and AEM-P resembled the concept of "Change-Point" of Hesketh and Brookes (2000), who inferred that there was a critical point of soil-test P, which alternates the relationship between P concentration in drainage water and soil-test P.

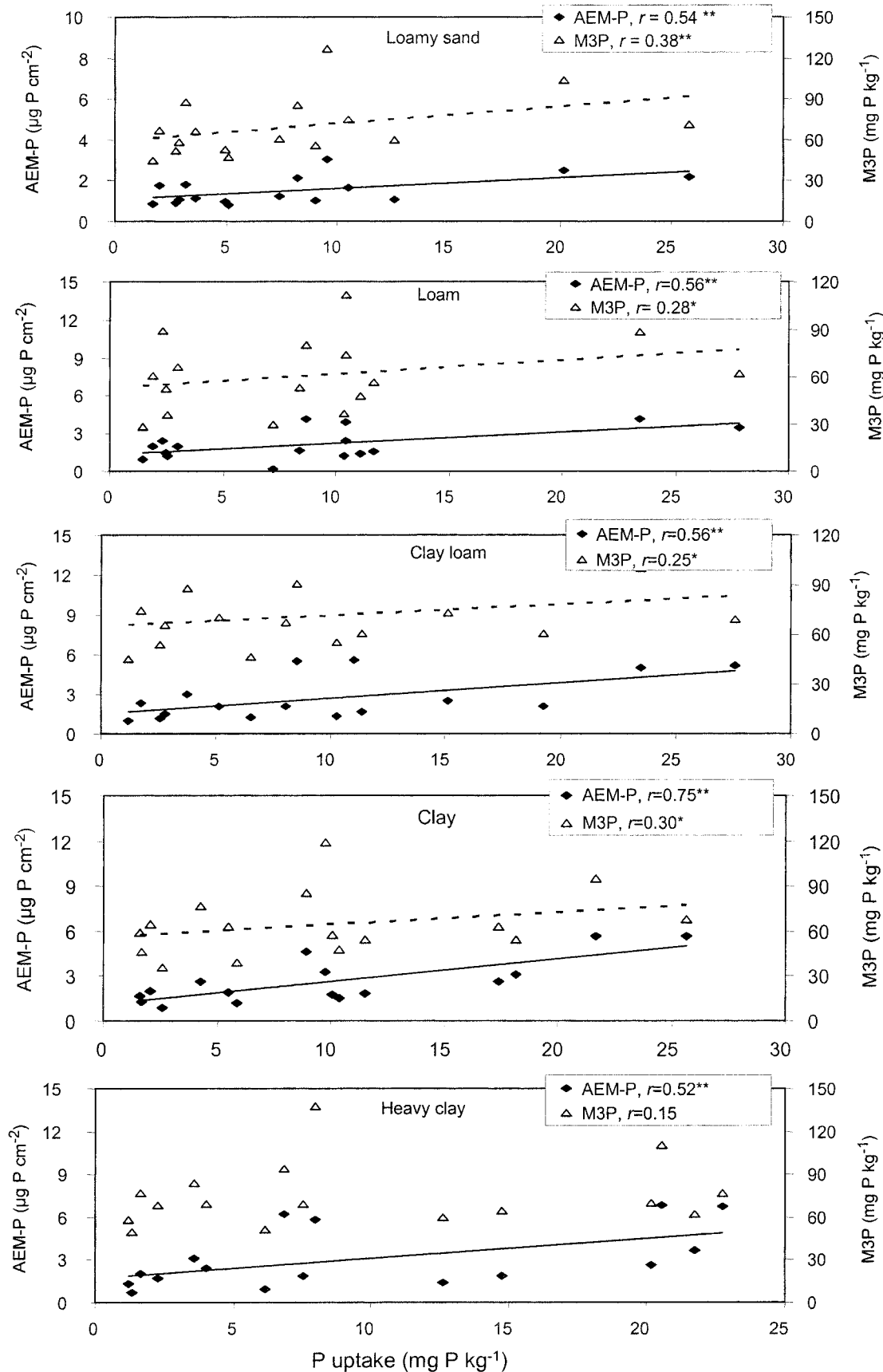


Fig. 3. Relationships between plant P uptake and anion-exchange membrane extractable P (AEM-P) or Mehlich-III extractable P (M3P) (*, **, significant at $P < 0.5$ and $P < 0.01$, respectively).

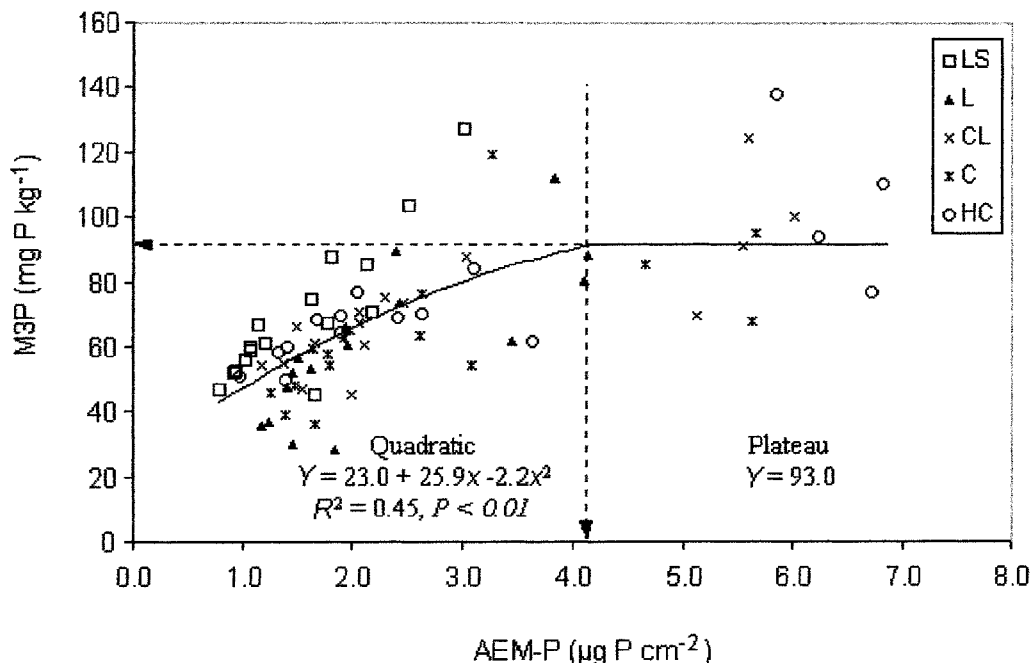


Fig. 4. The quadratic plateau relationship between anion-exchange membrane P (AEM-P) and Mehlich-III extractable P (M3P) contents across the tested soils and mineral fertilizer P (MFP) rates.

CONCLUSIONS

Previous studies have reported that the increase in chemical soil-test P per unit of MFP addition was strongly influenced by soil texture. Changes in AEM-P also followed MFP additions. The large influence of soil texture on changes in soil-test P and plant P uptake requires adjustments for soil texture in Humaquepts when assessing the P accumulation because of commercial fertilizers applied in excess of crop removal.

The quadratic plateau relationship between AEM-P and M3P showed a broad range of labile P where both indicators were closely related. The AEM-P was a valuable indicator of plant P availability in Humaquepts, especially when M3P exceeded 93 mg P kg^{-1} . Above 93 mg P kg^{-1} , the M3P method apparently lost efficiency in extracting a quantity of soil P that can be environmentally at risk. The use of AEM-P test is instrumental in identifying soils that are at sufficient P level for crops such as barley and soybeans. More importantly, the AEM-P test reflects P transfer in soil while minimizing disturbance, and could be indicative of P loss from soil to surface water for soils accumulating P from commercial fertilizers.

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