Agri-environmental models using Mehlich-III soil phosphorus saturation index for corn in Quebec

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Gilles Tremblay[2], Christine P. Landry[3], and Lotfi Khiari[1]

[1]*Departement of Soil Science and Agri-Food Engineering, Laval University, Quebec, Quebec, Canada G1K 7P4 (e-mail: leon-etienne.parent@sga.ulaval.ca);* [2]*Centre de Recherche sur les Grains inc. (CEROM), Saint-Bruno-de-Montarville, Quebec, Canada J3V 4P6;* [3]*Institut de Recherche et de Développement en Agroenvironnement inc. (IRDA), Quebec, Quebec, Canada G1P 3W8.*

Received 12 October 2005, accepted 14 August 2006.

Pellerin, A., Parent, L. E., Tremblay, C., Fortin, J., Tremblay, G., Landry, C. P. and Khiari, L. 2006. **Agri-environmental models using Mehlich-III soil phosphorus saturation index for corn in Quebec.** Can. J. Soil Sci. **86**: 897–910. Soil phosphorus (P), which is potentially a risk for environmental contamination, is currently interpreted using soil P saturation in North America. Our objective was to assess the ratio of P to aluminum (Al) in the Mehlich-III (M-III) soil test to build P requirement models for corn and soybean. We analyzed 129 corn and 19 soybean P fertilizer trials. For corn, the $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ ratio improved soil fertility classification compared with $\mathrm{P}_{\mathrm{M\text{-}III}}$ alone. The critical $\mathrm{P}_{\mathrm{M\text{-}III}}$ value as determined by the Cate-Nelson procedure was found to be 31.5 mg $\mathrm{P}_{\mathrm{M\text{-}III}}$ kg^{-1}, close to published values. The critical $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ ratios of 0.025 for > 300 g clay kg^{-1} soils and 0.040 for ≤ 300 g clay kg^{-1} soils differed significantly between the two soil groups. For $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ ratios above 0.214, there was no positive response to added P for all soils regardless of texture. Using published critical environmental $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ ratios of 0.076 for > 300 g clay kg^{-1} soils and 0.131 for ≤ 300 g clay kg^{-1} soils as benchmarks values, agri-environmental P requirement models were built using conditional expectations of 50 to 80% of computed optimum P values within a soil class. A validation study supported the low critical $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ ratios and the 50% conditional expectation model except for a high carbon soil which was outside the application range of the models. However, banded P decreased corn yield at four validation sites although the model predicted positive response to P. Soybean did not respond to P except at extremely low fertility levels ($(\mathrm{P/Al})_{\mathrm{M\text{-}III} } \le 0.02$) and behaved as a P-mining crop even in low-P soils. Corn-soybean rotations can reduce soil P to low $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ ratios with minimal agronomic risk.

Key words: Soil phosphorus saturation, Mehlich-III soil extraction method, soil fertility classification, soil texture, fertilizer P requirement model, corn, soybean

Pellerin, A., Parent, L. E., Tremblay, C., Fortin, J., Tremblay, G., Landry, C. P. et Khiari, L. 2006. **Modèles agroenvironnementaux de saturation en phosphore selon la méthode Mehlich-III pour les sols sous culture de maïs au Québec.** Can. J. Soil Sci. **86**: 897–910. Le P du sol, potentiellement à risque pour l'environnement, est de plus en plus interprété selon la saturation du sol en P pour effectuer des recommandations de fertilisation. Notre objectif était d'évaluer le rapport $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ et d'élaborer des modèles de réponse au P pour le maïs et pour le soya. Nous avons analysé 129 essais de fertilisation de maïs et 19 de soya. Pour le maïs, le rapport $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ a amélioré le classement des sols comparativement au $\mathrm{P}_{\mathrm{M\text{-}III}}$ seul. La valeur agronomique critique de 31,5 mg $\mathrm{P}_{\mathrm{M\text{-}III}}$ kg^{-1} était semblable aux valeurs publiées. Les valeurs $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ critiques de 0,025 pour les sols > 300 g argile kg^{-1} et 0,040 pour les sols ≤ 300 g argile kg^{-1} étaient significativement différentes entre les deux groupes de sol. Au-delà de 0,214, il n'y avait aucune réponse positive à l'ajout de P. En ajoutant les valeurs environnementales $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ critiques publiées de 0,076 (> 300 g argile kg^{-1}) et 0,131 (≤ 300 g argile kg^{-1}) comme balises, des modèles agroenvironnementaux ont été élaborés sous des hypothèses d'espérance conditionnelle de réponse de 50 à 80%. Le modèle 50% s'est situé le plus près des résultats de 16 essais de validation excluant un sol riche en C. Cependant, le P appliqué en bande a réduit le rendement du maïs sur quatre sites de validation où le modèle proposait d'ajouter du P. Le soya n'a pas réagi au P ajouté sauf en sol de très faible saturation ($(\mathrm{P/Al})_{\mathrm{M\text{-}III}} \le$ 0,02). Le maïs et le soya peuvent réduire le P accumulé dans le sol jusqu'à de bas niveaux de $(\mathrm{P/Al})_{\mathrm{M\text{-}III}}$ à de faibles risques agronomiques.

Mots clés: Saturation en phosphore du sol, méthode d'extraction du sol Mehlich-III, classement des sols selon leur niveau de fertilité, texture du sol, modèle de recommandation en engrais phosphaté, maïs, soya

Abbreviations: **B-I**, Bray-I soil extraction method; **B-II**, Bray-II soil extraction method; **CTU**, corn thermal unit; **DAP**, di-ammonium phosphate; **DRP**, dissolved-reactive phosphorus; **HS**, humic substances; **MAP**, mono-ammonium phosphate; **M-III**, Mehlich-III soil extraction method; $\mathbf{(P/Al)_{M\text{-}III}}$, Mehlich-III P saturation ratio as determined on a crude concentration basis (mg L mg^{-1} L^{-1}); **RY**, relative yield; **SPS**, soil phosphorus saturation; **STP**, soil test phosphorus

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The objective of phosphorus (P) fertilization is to add an adequate amount of P to produce the economic yield in regard to soil test P (STP) (Black 1993). However, P accumulation in soils from mineral and organic fertilizers may become a potential source of water pollution leading to eutrophication of surface waters by runoff and tile drainage (Sharpley et al. 1993; Sims et al. 1998; Beauchemin et al. 2003). Measures for reducing concentration of dissolved reactive P (DRP) in runoff and leaching waters are largely limited to preventing soil P accumulation (Sharpley 1995) by reducing P inputs or by planting crops with high P removal such as corn (*Zea mays* L.) and soybean [*Glycine max* L. (Merr.)] (Eghball et al. 2003). Soil test calibration research is still perceived as low priority despite its importance to farmers, agronomists, and the environment (Heckman et al. 2006) and for sustaining future generations of farmers (Black 1993). In general, fertilizer requirement models were interpreted using various concepts including buildup and maintenance based on soil enrichment, nutrient sufficiency based on soil test calibration and nutrient budget based on crop removal (Black 1993). Recently, fertilization concepts have been revisited considering both the agronomic and environmental issues of P accumulation in soils (Khiari et al. 2000; Sims et al. 2002).

The buildup and maintenance concept recommends the application of high rates of fertilizer P to achieve high STP levels in 1 or more years, followed by fertilizer P applications equivalent to crop removal regardless of the STP level (Black 1993). A P buildup recommendation is the rate of applied P necessary to increase STP by one unit after accounting for crop P removal. In Quebec, a rate of 3 kg fertilizer P ha^{-1} kg^{-1} P$_{\text{M-III}}$ ha^{-1} is needed to increase STP by one unit, based on data from Antoun et al. (1985) and Zhang et al. (1995). In Quebec corn production systems, increasing STP from medium STP (60 kg P$_{\text{M-III}}$ ha^{-1}) to high STP (150 kg P$_{\text{M-III}}$ ha^{-1}) [Conseil des Productions Végétales du Québec inc. (CPVQ) 1996] would require an application of ca. 270 kg P ha^{-1} on top of crop P removal over a short period of time. Assuming a corn yield of 10 Mg grain ha^{-1} and 2.7 kg P Mg^{-1} of grain at a moisture content of 150 g kg^{-1} equivalent to P concentration of 3.2 kg P Mg^{-1} of dry grain [Centre de référence en agriculture et agroalimentaire du Québec (CRAAQ) 2003], the maintenance recommendation would be 27 kg P ha^{-1} regardless of the STP level. The buildup and maintenance concept generally recommends more fertilizer than the nutrient sufficiency concept. However, if the buildup and maintenance concept reduces its target STP from a high to a medium STP level, a large quantity of P fertilizers could be saved by the farmer with little or no agronomic risk and the risk of water contamination by P loss would be reduced dramatically.

The probability of crop response to P as related to STP is the basis for implementing the nutrient sufficiency concept (Fitts 1955). The soils are grouped according to STP into below-optimum (very low to low), optimum (medium), and above-optimum (high to extremely high) fertility classes for making fertilizer recommendations. Below-optimum STP, soil P is considered to be deficient and there is a high to moderate probability of an economic yield response to applied P (Sims et al. 2002). More fertilizer P than that exported by the harvested portion of the crop is added in order to gradually increase STP levels to the optimum range. At optimum STP, soil P is considered adequate and P applications are rarely recommended. However, small amounts of P may be applied as starter fertilizer or for high-P-demanding crops to maintain the soil in the optimum range (Sims et al. 2002). Above optimum STP, soil P is considered more than adequate and no P should be applied because P does not limit crop yield and may be problematic for water P contamination (Sims et al. 2002). Nevertheless, some crops may respond to starter fertilizers even at high STP levels in cold and wet soils, but response is rarely expected at extremely high STP levels. Yield may be able to decline with fertilization at extremely high STP levels (Beegle et al. 1998). The maintenance concept is applicable only to the optimum range and the separation between below-optimum and optimum classes is the lower limit for the maintenance of soil fertility (Beegle et al. 1998). Thus, the lower limit of optimum range must be defined as accurately as possible for both agronomic and environmental reasons.

In order to manage both agronomic and environmental issues in crop systems, a single STP that would predict P risk of water contamination and crop response to P fertilization would be useful (Beegle et al. 1998). The DRP in runoff and leaching water was found to be highly correlated to water-extractable P and to soil P saturation (SPS) indices (Sharpley 1995; Yli-Halla et al. 1995; Pote et al. 1996, 1999; Maguire and Sims 2002a, b; Sims et al. 2002; Beauchemin et al. 2003). The SPS indices based on the Mehlich-III soil extraction method (M-III) as the (P/Al)$_{\text{M-III}}$ and the (P/[Al+Fe])$_{\text{M-III}}$ ratios were found to be more effective for prediction of P losses by runoff or leaching and for crop response to P fertilization, than P$_{\text{M-III}}$ alone in Quebec (Khiari et al. 2000; Pellerin et al. 2006) and the mid-Atlantic States (Maguire and Sims 2002a, b; Sims et al. 2002). However, soil texture is also an important classification criteria because it influences the M-III soil extraction method (Giroux and Tran 1985; Simard et al. 1991; Zheng et al. 2003). In Quebec soils, up to four textural groups were found to have specific environmental thresholds (Pellerin et al. 2006). Several studies showed that soil pH and texture, as well as Fe and Al oxyhydroxide contents can influence P uptake by crops, crop yield, and crop response to P fertilization (Olsen and Watanabe 1963; Cope and Rouse 1983; Cox and Lins 1984; Giroux and Tran 1985; Simard et al. 1991; Cox 1994; Jokela et al. 1998). Hence, there is a need to address agronomic and environmental P issues by integrating crop response, SPS index, and soil properties into a fertilization concept.

Our objectives were to present the theory of agri-environmental soil testing and to assess the (P/Al)$_{\text{M-III}}$ ratio in order to build and validate P agri-environmental requirement models for sustainable corn production and to evaluate the response to added P to soybean. We also investigated whether soil texture can influence crop response to P fertilization.

THEORY

Soil Calibration Studies

Several economic P rates can be obtained within the same soil fertility class because factors other than soil fertility such as moisture, temperature, hybrid, cultivar, rotations, pests, and weeds influence yield (Fitts 1955). Hence, a large number of trials must be conducted. In soil calibration studies, relative yields (RY) are used to standardize variability of crop responses to fertilization among soil type, location, and year (Whitney et al. 1985). The RY may be computed as yield in the control plot divided by maximum yield among P-treated plots at each site (Nelson and Anderson 1984). The positive or negative effects of fertilization can also be illustrated using the RY concept with a soil test partitioning diagram as described by Heckman et al. (2006).

The limits of the soil fertility classes can be derived from critical agronomic values using a soil test partitioning model (relation between RY and STP across sites). The critical agronomic value of the initial plateau in the soil test partitioning model is thought to be the separation between crop response and non-response (Beegle et al. 1998). Using deterministic non-linear models, the critical STP level generally corresponds to 95% RY with zero fertilization (Black 1993). Soil fertility classification can also be conducted on RY by maximizing the sums of squares among two to three soil fertility classes delineated by one or two critical STP values using the Cate-Nelson partitioning procedure (Nelson and Anderson 1984). This technique typically separates low and medium fertility classes near 80% RY (Black 1993).

Cope and Rouse (1983) suggested that the high STP upper limit would be two times the medium STP upper limit and four times the very low STP upper limit. Instead of using these mathematical relationships, critical environmental STP values can be used to provide new benchmarks for agri-environmental P requirement models (Khiari et al. 2000). In Quebec, Pellerin et al. (2006) defined environmental thresholds for up to four textural groups, with $(P/Al)_{M\text{-}III}$ ratios varying from 0.058 to 0.153 in acid to near neutral mineral soils varying in texture and genesis. In an agri-environmental approach, soil fertility classes are defined using critical agronomic STP values as agronomic benchmarks and critical environmental STP values to account for environmental risk (Khiari et al. 2000).

In each soil fertility class, the response to a starter fertilizer P can be evaluated. Using the within-class standard deviation of RYs in each soil fertility class, the mean of RY is compared with an expected mean of 100% for non-response to a starter fertilizer P. Thereafter, the power of making a good decision to fertilize is computed. Power, that is one minus Type II (β) error, is the probability that a statistical test will identify treatment's effect if it actually exists (Hair et al. 1995). In general, the Power test must be high (≥ 0.80) to reject the null hypothesis (Hair et al. 1995). Should the Power test be high, crops in this fertility class require P for maximum yield even though Type I error does not detect treatment any significant effect of added P at a given site.

Response Pattern

In most studies, economic P rates are obtained from response curves described by plateau, linear, linear- or quadratic-plateau or polynomial models. For a regressive yield pattern (yield reduction with added P) or a plateau model, the economic P rate is zero. For a linear plateau response model, economic P rate is at the intersection between the linear response and yield plateau if the slope of the linear trend exceeds the price ratio, and at zero if it does not. The proper selection of non-linear crop response models has a significant influence on the value of the economic P rate and a non-linear response must be carefully examined to avoid selecting excessively high economic P rates (Dahnke and Olson 1990). Since quadratic models tend to overestimate optimum P rates, their economic P rate is further constrained by setting the first derivative of the quadratic equation to the ratio of fertilizer cost to product price (Nelson et al. 1985).

Economic P rates can be ranked in an ascending order within a soil fertility class and the P rate recorded for a selected conditional expectation (e.g., 50th, 60th, 70th, or 80th percentile) (Isaaks and Srivastava 1989; Khiari et al. 2000). The 80th percentile of ascending P rates means that 80% of economic P rates in that fertility class are lower or equal to the recorded P rate. Using the 80th percentile or less eliminates outliers, especially those derived from some quadratic equations or from studies which use large P rate intervals. The P rate for the selected percentile within a given fertility class is paired to the median STP value in that class to build a continuous P requirement model.

MATERIALS AND METHODS

Soil and Trial Description

Yields and soil samples were collected from 129 trials on grain or silage corn and 19 trials on soybean conducted in Quebec across 57 soil series (55 on corn and 5 on soybean, 3 overlapping soil series). Soils were classified as Dystric Brunisol, Eutric Brunisol, Melanic Brunisol, Gleysol, Humic Gleysol, Humo-Ferric Podzol, Ferro-Humic Podzol, and Regosol [Agriculture Canada Expert Committee on Soil Survey (ACECSS) 1987].

In corn trials, large plots (minimum of 200 m long and four to six rows wide) were used to simulate operations in commercial fields (measured plant density: 70 000 to 94 000 corn plants ha^{-1}). There were one or two replications at each commercial site. Corn yields were measured by hand sampling five 3-m rows within plot areas 25 m long and two to four rows wide selected in the spring for uniform soil characteristics (pH, texture, carbon content and landscape position) and, thereafter, for representative plant growth within those areas (seasonal monitoring of plant height, plant density and foliage greenness using a SPAD-502 instrument). For corn and soybean on experimental farms, we used small plots, which were 5 to 25 m long and four to eight rows wide for corn and 0.9 to 4.5 m wide for soybean (plant density averaging 74 000 corn plants ha^{-1} and 450 000 soybean plants ha^{-1}). For each crop, there were two to five replications at each site, and treatments were arranged in randomized-plot or completely randomized-block designs. Corn yields were measured by hand sampling (two central rows, 3 to 5 m long) or using a plot combine while soybean harvesting was conducted with a plot combine. Grain yield was expressed on the basis of a moisture content of 150 g kg^{-1}. Soybean response to added P was evaluated from 9 field P response trials from Tremblay and Beausoleil (2000) and 10 new field P response trials on low- to medium-fertility P levels in the St-Lawrence Lowlands during the 1997–1999 period. There were three to five P rates (0, 13, 26, 31–39, up to 52 kg P ha^{-1}). Economic P rates for soybean were obtained from plateau (11 trials), linear (5 trials) and polynomial (3 trials) models.

In the corn study, data from 69 field P response trials under conventional tillage were re-evaluated [Barnett 1969; Dionne et al. 1977 (silage corn); Bationo 1979; Guertin et al. 1997; Giroux and Guertin 1998]. We conducted 52 new field P response trials using four P rates (0, 8, 16 and 32 kg P ha^{-1}) under conventional tillage (1999–2001) and 8 new field P response trials using four P rates (0, 9, 17 and 35 kg P ha^{-1}) under no-till or ridge tillage (1998–1999). Since economic P rates were not statistically different between conventional and reduced tillage for the same soil fertility class, corn response models were built across tillage practices. For corn trials conducted before 1979, P fertilizers were applied either broadcast or in band. Later on, P fertilizers were banded 5 cm beside and 5 cm below the seed. For fertilizer trials carried out before 1989, soil P was extracted by the Bray-II (B-II) method (Bray and Kurtz 1945). Fertilizer trials conducted before 1989 were used only to derive economic P rates in the low-fertility classes due to lack of recent P trials in these classes. Trials conducted before 1989 were thus discarded in higher fertility classes since recent P trials were in sufficient number to build the P fertilizer requirement models with new hybrids (measured site potentials between 7.5 and 14.0 Mg ha^{-1}). Hence, 92 trials (32 earlier trials and 60 new trials) were retained to build P requirement models. Economic P rates for corn were obtained from plateau (15 trials), linear (16 trials), linear-plateau (35 trials) and polynomial (26 trials) models.

Hybrids of grain and silage corn were confounded with site effect. However, Eghball et al. (2003) found significant corn hybrid effects on P concentration in the grain and on P removal by the crop for 11 hybrids and one line grown on the same sites for 2 yr. The P removal was proportional to grain yield across corn hybrids, but the direct effect of added P on hybrid yield was not tested. Teare and Wright (1990) classified corn hybrids by their response to starter P fertilizer as those that resulted in a positive change, a negative change or no change, but this should be quantified for each hybrid in separate experiments especially in high P testing soils where no starter fertilizer P may be recommended (Sims et al. 2002). In our study, as elsewhere (Heckman et al. 2006), we assumed that no interaction occurred between hybrid and site for corn response to added P. We concur, however, that a given hybrid may contribute more than another to P removal in the P budget supporting a soil P maintenance policy.

Validation Study with Grain Corn

A validation study was conducted on 8 sites in 2002, 8 sites in 2003, and one site in 2004 with 12 corn hybrids grown on 11 soil series. The soils were Gleysols (Ste-Rosalie, St-Urbain, St-Blaise, Ste-Barbe, La Baie, and St-Aimé series), Brunisols (St-Valentin and St-Mathieu series), and Podzols (St-Jude, St-Sylvère, and Sorel series) (ACECSS 1987). Corn hybrids, varying between 2450 and 3000 UTM were: Pioneer 27M3, 37H27, 38G17, 38P05, 39A26, 39D82; Dekalb 221, 29–95, and 42–71; NK 2555 Bt, and 3030 Bt; Codisem 250. Seeding was performed between Apr. 21 and May 27, and crops were harvested between Oct. 15 and Oct. 24. Plots were 8 m long and six rows wide. Row spacing was 0.76 m. Plant density evaluated at harvest varied between 52 815 and 90 686 plants ha^{-1}. Plots were hand-harvested in four central rows over a length of 4 m. At each site, there were three P rates (0, 20, and 40 kg P ha^{-1}) and three replicates. The fertilizer sources were mono- (MAP) or di-ammonium (DAP) phosphate, and mixtures of MAP or DAP with dry swine manure (dry swine manure in proportions of 25% to 100% by weight combined with DAP or MAP) or peat (20% peat by weight combined with DAP or MAP), totalling 11 treatments including the control treatment without P. However, only the conventional fertilizers MAP and DAP were considered for testing yield response to added P. The cultural practices used by the cooperating farmer were followed. The plots were arranged in a randomized block design.

Soil Analysis

Composite soil samples made of 8–10 cores per plot were collected in the plough layer (0–20 cm) before applying the fertilizer treatments. Soil samples were dried in a forced air oven at 50°C for 24 h, then sieved to < 2 mm. Soil texture was determined using the hydrometer method (Gee and Bauder 1986). Soil pH was measured in distilled water using a soil:solution ratio of 1:1 (vol/vol). The P, Al and Fe were extracted following the M-III procedure (Mehlich 1984). Briefly, we scooped and weighed 3 mL of soil, extracted it using 30 mL of M-III solution and filtered through Whatman no. 42 paper (Whatman, Clifton, NJ). The $P_{M\text{-}III}$ was quantified by colorimetry according to Laverty (1963). The $Al_{M\text{-}III}$ and $Fe_{M\text{-}III}$ were determined using an atomic absorption spectrophotometer. For fertilizer trials conducted before 1989, soil P has been extracted by the B-II method (Bray and Kurtz 1945). We used the Khiari et al. (2000) equation to convert $P_{B\text{-}II}$ into $P_{M\text{-}III}$. For fertilizer trials conducted before 1989, $Al_{M\text{-}III}$ content was obtained by soil series in a Quebec soil survey (Tabi et al. 1990). The $Al_{M\text{-}III}$ content was considered to be an intrinsic soil property since the within-series coefficient of variation was 10% (Tabi et al. 1990). The $P_{M\text{-}III}$ and the $(P/Al)_{M\text{-}III}$ ratio were converted into inductively coupled-argon plasma values using equations in Khiari et al. (2000) developed from soils that have a large range in clay content (10–730 clay g kg^{-1}), water pH (4.6–7.0), carbon content (3–79 g C kg^{-1}), and $(P/Al)_{M\text{-}III}$ ratios (0.005–0.617 mg L mg^{-1} L^{-1}) and having undergone podzolization or gleyzation during their development (100 soils; $R^2 = 0.99$). In this study, the $(P/Al)_{M\text{-}III}$ ratio is a crude concentration ratio (mg L mg^{-1} L^{-1}).

Statistical Analysis

Statistical analyses were conducted using the SAS package (SAS Institute, Inc. 2001). Results were analyzed yearly using a split plot design with sites as main plot units and P treatments as sub-plot units using GLM or PROC MIX (SAS Institute, Inc. 2001). The soil fertility classification was conducted using RY as in Mallarino (2003) and Heckman et al. (2006) (computing RY by dividing yield in the control by either plateau or maximum yield in fertilized treatments). Partitioning between soil fertility classes was obtained iteratively by the Cate-Nelson procedure (Nelson and Anderson 1984) using a Fortran package (Microsoft 1993).

We compared critical agronomic values of corn grown in two contrasting textural groups as defined by Pellerin et al. (2006). The two contrasting textural groups were ≤ 300 g clay kg^{-1} and > 300 g clay kg^{-1} soils (Pellerin et al. 2006). Simard et al. (1991) found that corn required less fertilizer P in fine- than in coarse-textured Quebec soils. The difference between critical STP values in both soil textural groups was tested using a jackknife technique (Wang et al. 1997). Briefly, a dataset $x = (x_1,\ldots, x_n)$ (here RY) of independently and identically distributed samples of unknown distribution is iterated (Nelson and Anderson 1984) after deleting the ith observation $x_{(i)} = (x_1,\ldots,x_{i-1},x_{i+1},\ldots, x_n)$. Be $s(x)$ is the real-valued statistic of interest (here the Cate-Nelson critical value) and let $s_{(i)} = s(x_{(i)})$ be the corresponding deleted point for the statistic of interest. The jackknife estimate for standard error of $s(x)$ is defined as follows:

$$\hat{se}_{jack}\{s\} = \left[\frac{n-1}{n}\sum_{i=1}^{n}(s_{(i)} - s_0)^2\right]^{1/2} \quad (1)$$

where n is the number of observations and $s_0 = \sum_{i=1}^{n} s_{(i)} / n$.

The $\hat{se}_{jack}\{s\}$ was used to compute a two-tail Student's t test to test differences between critical STP values in soil groups.

For computing economic P rates, the first derivative of the quadratic equation (dy/dx) was fixed to the ratio of fertilizer cost to product price of 12.1 for grain corn, 29.5 for silage corn and 5.8 for soybean, where y is yield in kg ha^{-1} of grain at 150 g kg^{-1} moisture content and x is fertilizer rate in kg P ha^{-1}. The cost of 1 kg of P was obtained from local fertilizer dealers in 2002. The 1996–2001 price average paid to the farmer for corn and soybean was obtained from the Fédération des producteurs de cultures commerciales du Québec (2002).

In validation experiments, we conducted linear and quadratic contrasts for added P effects across P sources when the source effect was not significant; otherwise, the polynomial contrasts were conducted on conventional fertilizer sources (MAP or DAP). Where contrasts were significant, we determined the economic P rates as above. Economic P rates were compared with optimum P rates derived from the P requirement models. Some interactions of hybrids with year and soil in response to P could be evaluated. Hybrid Pioneer 39D82 was grown on similar soils on the same farm in 2002, 2003, and 2004 (sites 8, 16 and 17), providing an evaluation of the year by rate interaction. Hybrid Pioneer 27M3 was grown at two locations in 2003 differing in soil classification but with small difference in $(P/Al)_{M\text{-}III}$ ratio (sites 13 and 14), thus allowing a gleysol vs. podzol comparison within the same textural group. In 2003, hybrid NK 3030 Bt was grown on the two textural soil groups within the same soil classification (sites 10 and 15).

CTU were computed as follows:

$$DCTU = \frac{Y_{\min} + Y_{\max}}{2} \quad (2)$$

where DCTU is daily corn thermal unit (unitless) and

$$Y_{\min} = 1.80(T_{\min} - 4.4) \quad (3)$$

and

$$Y_{\max} = 3.33(T_{\max} - 10) - 0.084(T_{\max} - 10)^2 \quad (4)$$

where $T_{\min}$ is the minimum daily temperature and $T_{\max}$ is maximum daily temperature in °C.

The computation of Eq. 2 starts in the spring when air temperature reaches 12.8°C and ends in the fall when air temperatures reach 5.6°C (Dubé et al. 1984; CRAAQ 2002).

RESULTS AND DISCUSSION

Soil Test Partitioning Models

Soil characteristics are presented in Table 1. The clay content ranged between 49 and 682 g kg^{-1}, the $(P/Al)_{M\text{-}III}$ ratio varied between 0.005 and 0.472 and carbon content ranged from 9.9 g kg^{-1} to 59.3 g kg^{-1}. Thus, the P requirement models covered a large spectrum of soil characteristics. Corn critical agronomic STP values as $P_{M\text{-}III}$ and $(P/Al)_{M\text{-}III}$ ratios obtained iteratively using the Cate-Nelson procedure (Nelson and Anderson 1984) are presented in Fig. 1. The critical STP value separating low- and medium-fertility classes was found near 80% RY as in Black (1993).

The critical agronomic value was found to be 31.5 mg $P_{M\text{-}III}$ kg^{-1} or 36.4 mg $P_{M\text{-}III}$ L^{-1} of scooped soil (average bulk density ≈1.15 g L^{-1}) between low and medium soil fertility classes (Fig. 1), slightly above 27 mg $P_{M\text{-}III}$ L^{-1} used by the Quebec provincial authority (CPVQ 1996). An upper critical value of 218.6 mg $P_{M\text{-}III}$ kg^{-1} or 252.6 mg $P_{M\text{-}III}$ L^{-1} of scooped soil delineated high from extremely high P fertility classes. Above 252.6 mg $P_{M\text{-}III}$ L^{-1}, there was an apparent regressive pattern for five data points (i.e. corn yield declined with fertilization).

In comparison, Mallarino (2003) found critical values of 20 mg $P_{M\text{-}III}$ kg^{-1} using the Cate-Nelson approach and 32 mg $P_{M\text{-}III}$ kg^{-1} using the linear-plateau method for soil tests not exceeding 85 mg $P_{M\text{-}III}$ kg^{-1} in Iowa soils. Mallarino et al. (1991) did not find any economic response of corn and soybean to P during 11 consecutive years of alternating crops in

Table 1. Range of soil properties in the plough layer (0–20 cm) for the 129 corn and 19 soybean fertilizer trials

Soil property	Range	Mean	Standard deviation
pH	5.0–7.4	6.2	0.6
		($g\ kg^{-1}$)	
Clay	49–682	259	149
C	9.9–59.3	21.8	8.8
		($mg\ L^{-1}$)	
$P_{M\text{-}III}$	6.9–336.9	81.9	74.4
$Al_{M\text{-}III}$	423.2–1842.2	1051.5	282.9
		($mg\ L\ mg^{-1}\ L^{-1}$)	
$(P/Al)_{M\text{-}III}$	0.005–0.472	0.085	0.083

Iowa on soil testing 28 mg P kg^{-1} as Bray-I (B-I) method [28 mg $P_{M\text{-}III}$ kg^{-1} using conversion equations in Hanlon and Johnson (1984), Wolf and Baker (1985) and Tran et al. (1990)]. Bullock et al. (1993) found no response of corn to P in Illinois on a soil testing 68 mg $P_{B\text{-}I}$ kg^{-1} [63 mg $P_{M\text{-}III}$ kg^{-1} using conversion equations in Hanlon and Johnson (1984), Wolf and Baker (1985) and Tran et al. (1990)]. On the other hand, Heckman et al. (2006) reported either positive or negative effects of added P on corn response up to 418 mg $P_{M\text{-}III}$ kg^{-1} in the northeast USA.

Critical $(P/Al)_{M\text{-}III}$ ratios were 0.029 (low- to medium-fertility classes) and 0.214 (high to extremely high fertility classes) across trials (Fig. 1). The $(P/Al)_{M\text{-}III}$ ratio increased the number of cases (n = 11) in the extremely high P fertility class compared with $P_{M\text{-}III}$ alone (n = 5), thus improving soil fertility classification for non-responsive corn (Fig. 1). Heckman et al. (2006) also reported either positive or negative effects of fertilizer P on corn response up to a $(P/Al)_{M\text{-}III}$ ratio of 0.28 in the northeast USA.

Corn critical agronomic $(P/Al)_{M\text{-}III}$ ratios were found to be 0.040 and 0.217 for ≤ 300 g clay kg^{-1} soils, compared with 0.025 and 0.214 for > 300 g clay kg^{-1} soils (Fig. 2). Critical agronomic $(P/Al)_{M\text{-}III}$ ratios of 0.025 and 0.040 were statistically different using a jackknife technique (Wang et al. 1997) (Table 2). The critical agronomic $(P/Al)_{M\text{-}III}$ ratios of 0.214 and 0.217 were not statistically different. In a 9-yr phosphorus study, corn yield potential decreased despite P fertilization, as the $(P/Al)_{M\text{-}III}$ ratio dropped from 0.043 to 0.035 in soil with ≤ 300 g clay kg^{-1} in the St-Lawrence Lowlands (Tremblay et al. 2003). The low-P status of 0.035 was below the critical agronomic threshold of 0.040 obtained above for ≤ 300 g clay kg^{-1} soils. This long-term experiment supported the threshold value of 0.040 for sustaining the corn production with regard to STP in ≤ 300 g clay kg^{-1} soils.

Corn response to P was significant in the low and medium to high P soil fertility classes defined by the $(P/Al)_{M\text{-}III}$ ratio, as shown by the Power test of 0.97 to 1.00 (Table 3), yield gain varying from 5.1 to 28.9% in fertilized plots compared with control. In the extremely high P soils ($(P/Al)_{M\text{-}III}$ ratio > 0.214), the power was 0.00–0.01 and control plots produced higher yields than P-treated plots at 9 out of 11 sites; at those 9 sites, yield loss with added P, although non-significant, varied from 1.7 to 4.6% (Table 3).

No soybean critical agronomic STP value could be determined for $P_{M\text{-}III}$ or $(P/Al)_{M\text{-}III}$ ratio since RY varied between 93 and 103%, averaging 99% (Fig. 2). Soybean crops did not respond to fertilizer P except in two soils showing $(P/Al)_{M\text{-}III}$ ratios of 0.010 and 0.014. In general, soybean does not respond to fertilizer P at high to excessively high STP, but could respond in soils with low or extremely low STP levels (DeMooy et al. 1973; Bharati et al. 1986; Mallarino et al. 1991; Tremblay and Beausoleil 2000). The critical agronomic $(P/Al)_{M\text{-}III}$ ratios were thus driven by corn rather than soybean in corn-soybean rotations.

Environmental Risk

Lower critical agronomic $(P/Al)_{M\text{-}III}$ ratios of 0.025 and 0.040 were far below the environmental limit of 0.076 and 0.131 for eutrophication (0.03 mg total-P L^{-1}) in tile drain water for > 300 g clay kg^{-1} and ≤ 300 g clay kg^{-1} soils, respectively (Pellerin et al. 2006). Upper critical agronomic $(P/Al)_{M\text{-}III}$ ratios of 0.214 and 0.217 exceeded the environmental thresholds. Hence, including environmental thresholds in the agri-environmental model as benchmarks between critical agronomic values should prevent excessive P accumulation in the soil.

Phosphorus Requirement Models

Environmental (Pellerin et al. 2006) and agronomic (this study) thresholds were combined to build agri-environmental P requirement models by textural group based on the $(P/Al)_{M\text{-}III}$ ratio and the nutrient sufficiency concept (Table 4). Lower agronomic $(P/Al)_{M\text{-}III}$ ratios were the upper limits of the low-fertility classes. Critical environmental $(P/Al)_{M\text{-}III}$ ratios were the upper limits for the medium-high fertility classes. Between low and medium-high classes, an additional class was included (medium–low-fertility group) using the median SPS value between the low and medium-high classes. The higher critical agronomic $(P/Al)_{M\text{-}III}$ ratios were the upper limits for the high fertility classes. The P requirement models showing 50 or 80% conditional expectations among recorded economic P rates, and the attenuated models are presented in Fig. 3. The attenuated model is a new approach developed in this study since, as SPS increases, the agronomic risk of not fertilizing the crop decreases while the risk of P pollution through erosion, runoff or leaching increases. The attenuated model is made more restrictive as environmental risk increases. For the low soil fertility class, the economic P rate for 80% conditional expectation was selected since $(P/Al)_{M\text{-}III}$ was low and the P fertilization should exceed crop removal to build up soil fertility at low environmental risk. As a measure against P accumulation, the 70% conditional expectation was chosen for the medium-low fertility class, and the 60% conditional expectation for the medium-high fertility class. The economic P rate for 50% conditional expectation or median soil conditions was applied to high to extremely high fertility classes to prevent applying too much P above critical environmental thresholds.

The P requirement models showed that, for comparable $(P/Al)_{M\text{-}III}$ ratios, corn required less fertilizer P in fine- than in coarse-textured soils (Fig. 3) in agreement with Simard et al. (1991). A yield target can be reached at a lower STP level as clay content increases (Cox and Lins 1984; Lins and Cox

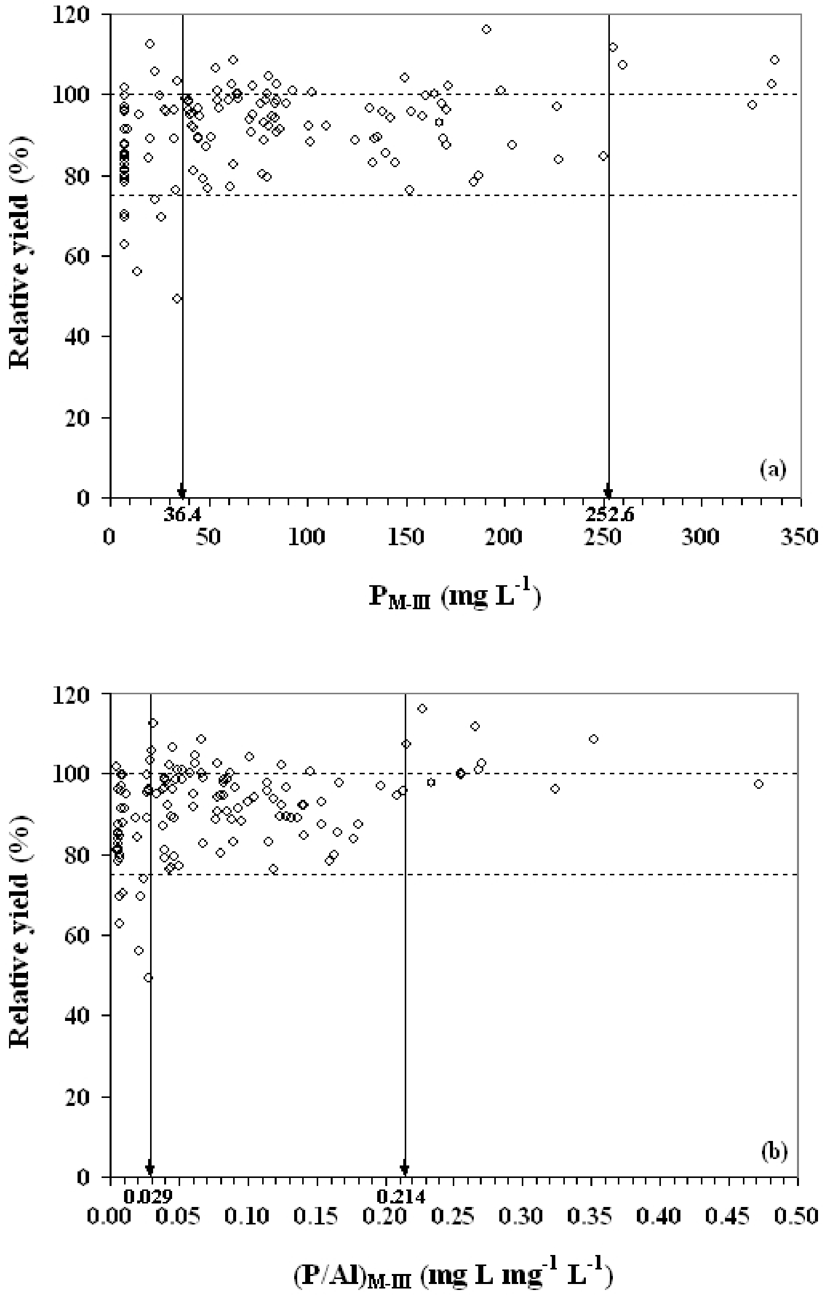

Fig. 1. Soil test partitioning models for corn (n = 129) for (a) the $P_{M\text{-}III}$ and (b) the $(P/Al)_{M\text{-}III}$ ratio.

1989), as found here. Since porous system diffusion coefficient in bulk solution is smaller in coarse- than in fine-textured soils (Olsen and Watanabe 1963), a higher soil solution P concentration is required in coarse-textured soils for a given amount of available P to reach the roots (Lins and Cox 1989).

Corn can be fertilized at P rates lower than P removal even at low $(P/Al)_{M\text{-}III}$ ratios, without any yield loss. For a Quebec average yield of 7.3 Mg ha^{-1} over the past 10 yr (Institut de la Statistique du Québec 2005) and assuming P removal rate of 2.7 kg P Mg^{-1} of grain at trade moisture content of 150 g kg^{-1} (CRAAQ 2003), P removal would be 20 kg P ha^{-1}. In the ≤ 300 g clay kg^{-1} soils, this requirement was reached at $(P/Al)_{M\text{-}III}$ ratios of 0.029, 0.053, and 0.059 for the 50% conditional expectation, the attenuated, and the 80% conditional expectation models, respectively. For the > 300 g clay kg^{-1} soils, the models recommended 20 kg P ha^{-1} at $(P/Al)_{M\text{-}III}$ ratios of 0.010, 0.038, and 0.041 for the 50% conditional expectation, the attenuated, and 80% conditional expectation models, respectively, hence at $(P/Al)_{M\text{-}III}$ ratios much lower than environmental thresholds.

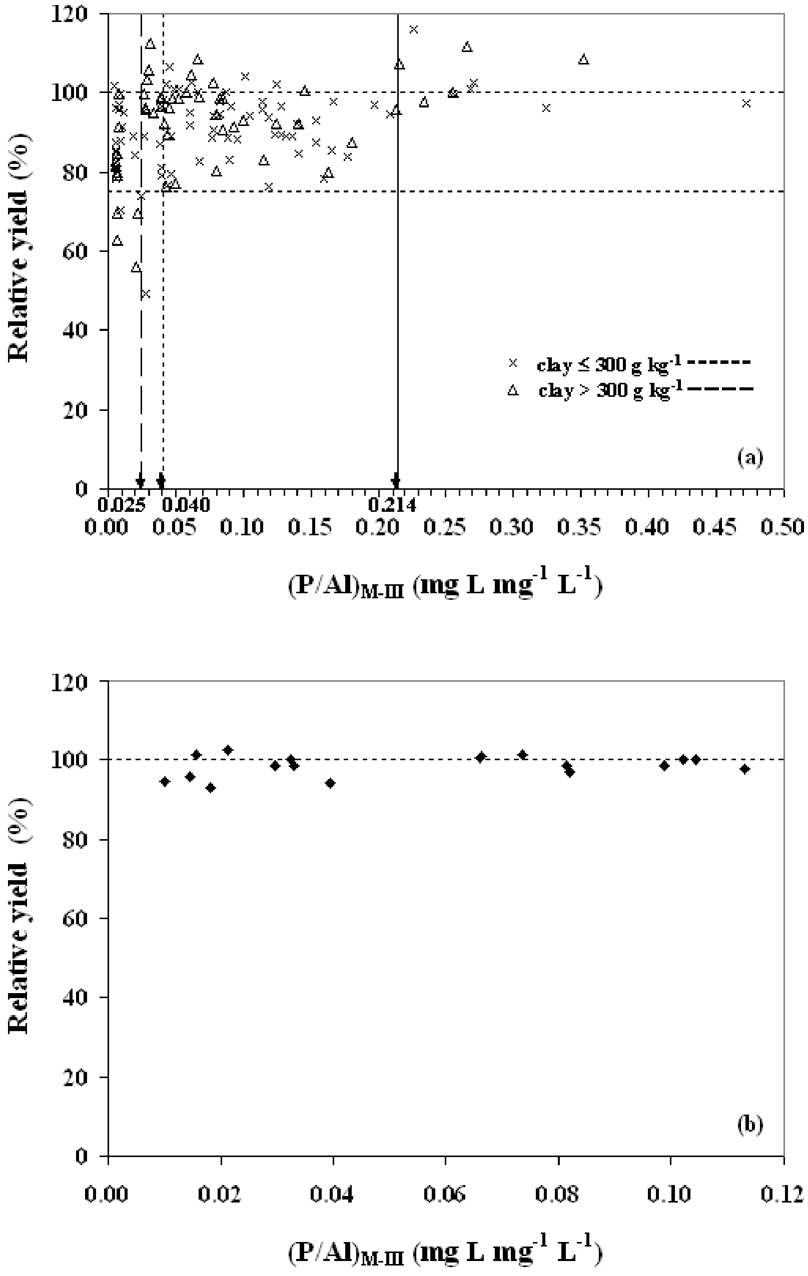

Fig. 2. Soil test partitioning models for the $(P/Al)_{M\text{-}III}$ ratio by textural group (a) for corn (*n* = 129) and (b) for soybean (*n* = 19).

For the extremely high soil fertility classes with $(P/Al)_{M\text{-}III}$ ratio > 0.214, there were no significant crop responses to added P across sites (Table 3), and the environmental risk of applying P was extremely high. Soil P reserve alone appeared adequate to sustain plant growth. No P fertilizer should be applied until the $(P/Al)_{M\text{-}III}$ ratio decreases below the extremely high soil fertility class. Other studies showed no significant corn response to P in soils testing high in P (Mallarino et al. 1991; Bullock et al. 1993; Guertin et al. 1997; Giroux and Guertin 1998). As environmental risk increases, most efficient crop rotations in terms of P removal, fertilizer P source and P application method should be used. Therefore, a hybrid that is less sensitive to banded P could be selected. Some corn hybrids responded positively to P starter fertilizer even in high P testing soils (Teare and Wright 1990; Gordon et al. 1997). However, no data are available in Quebec on the interaction between corn hybrids and P requirements.

Above the medium-low soil fertility classes for corn and for $(P/Al)_{M\text{-}III}$ ratios lower than the critical environmental values, P requirement was below P removal for all of the P requirement models (Fig. 3). Thus, in sensitive watersheds, the $(P/Al)_{M\text{-}III}$ ratio could be maintained above critical agro-

Table 2. Jackknife estimates of the mean and standard error for corn critical agronomic $(P/Al)_{M\text{-}III}$ ratios for two textural groups using a jackknife technique

	$(P/Al)_{M\text{-}III}$					
Critical values	Mean s_0	Standard error $\hat{s}e_{jack}\{s\}$	Mean $s_{()}$	Standard error $\hat{s}e_{jack}\{s\}$	Degrees of freedom	Student *t* value
	(mg L mg^{-1} L^{-1})					
	clay > 300 g kg^{-1}		*clay ≤ 300 g kg^{-1}*			
Lower	0.024	0.016	0.040	0.009	66.3	6.15***
Upper	0.211	0.185	0.216	0.030	41.7	0.19 NS

*** Significant at $P < 0.001$; NS, is not significant.

Table 3. Power tests of corn response to added P by textural group in Quebec or computed using the Heckman et al. (2006) data from Northeast USA

P soil fertility class	$(P/Al)_{M\text{-}III}$	*n*	Relative yield Mean	Relative yield Standard deviation	Yield gain[z] Mean	Power[y]
	(mg L mg^{-1} L^{-1})		(%)			
			clay ≤ 300 g kg^{-1}			
Low	0–0.040	26	86.2	11.0	17.2	1.00
Medium to high	0.041–0.217	45	92.4	7.5	8.4	1.00
Extremely high	> 0.217	6	102.1	7.1	–1.7	0.01
			clay > 300 g kg^{-1}			
Low	0–0.025	11	77.8	12.7	28.9	1.00
Medium to high	0.026–0.214	36	95.1	8.3	5.1	0.97
Extremely high	> 0.214	5	105.1	5.9	–4.6	0.00

[z] Yield gain (%) = 100[maximum yield (Mg ha^{-1}) – control yield (Mg ha^{-1})]/[control yield (Mg ha^{-1})].

[y] Power tests for relative yield conducted under the null hypothesis that expected mean relative yield was 100% for no response to P starter fertilizer (power must exceed 0.80 to reject the null hypothesis).

Table 4. Fertility classes and environmental risk groups for two textural groups for corn as defined by the $(P/Al)_{M\text{-}III}$ ratio

Soil fertility class or Environmental risk group	$(P/Al)_{M\text{-}III}$	
	(mg L mg^{-1} L^{-1})	
	clay ≤ 300 g kg^{-1}	*clay > 300 g kg^{-1}*
Low	≤ 0.040[z]	≤ 0.025[z]
Medium-low	0.041–0.086	0.026–0.050
Medium-high	0.087–0.131[y]	0.051–0.076[y]
High	0.132–0.217	0.077–0.214
Extremely high	> 0.217[x]	> 0.214[x]

[z] Critical values derived from soil test partitioning models: lower critical agronomic values.

[y] Critical values derived from environmental models (Pellerin et al. 2006).

[x] Critical values derived from soil test partitioning models: higher critical agronomic values.

nomic values and below critical environmental values; i.e., in the medium-low and medium-high soil fertility classes, without agronomic risk. A nutrient sufficiency concept, which would increase $(P/Al)_{M\text{-}III}$ ratio to the medium-low soil fertility classes and maintain or reduce it when soils reach the medium-high fertility classes would be an effective strategy compared with the former buildup and maintenance concept of a high soil fertility level with heavy fertilization and annual additions accounting for P removal and P loss. However, further studies are needed to determine P additions to maintain $(P/Al)_{M\text{-}III}$ ratio in the medium fertility classes in corn-soybean systems (Giroux 2003).

Validation Study with Grain Corn

The validation sites showed a $(P/Al)_{M\text{-}III}$ range from 0.060 to 0.095 in > 300 g clay kg^{-1} soils and between 0.017 and 0.291 in ≤ 300 g clay kg^{-1} soils (Table 5). Hybrid effects could not be detected since none of the sites that had a hybrid comparison (8 vs. 16 vs. 17); (13 vs. 14); and (10 vs. 15) were responsive to added P. Corn responded to added P at $P \le 0.05$ or $P \le 0.10$ at three sites in 2002 and three sites in 2003 (Table 6). Of the five sites with > 300 g clay kg^{-1}, four showed no significant response and one site (16) had a yield decrease with added P. At 12 sites in ≤ 300 g clay kg^{-1} soils, seven showed no significant response and five, either a yield increase (sites 5 and 11) or decrease (sites 2, 3 and 13). Excluding site 5 (see below), the 50% conditional expectation model was the most successful in predicting P requirements. A successful model means that the P requirement predicted by the conditional expectation model was higher than the economic P computed from the response curve in the validation study. Excluding site 5, P fertilization was required at only one site with a $(P/Al)_{M\text{-}III}$ ratio of 0.025 (Table 6), within the highly responsive range for ≤ 300 g clay kg^{-1} soils (Table 3). The agronomic thresholds of 0.025 for > 300 g clay kg^{-1} soils and 0.040 for ≤ 300 g clay kg^{-1} soils were thus confirmed by the validation study. However, significant yield loss occurred with added P at sites 2, 3 and 13 (≤ 300 g clay kg^{-1} soils) and 16 (> 300 g clay kg^{-1} soils) indicating that the banding of fertilizer P may fail to increase corn yield as predicted by the models (Fig. 3) for soils testing medium-low to high in P (Table 4). Data from Heckman et al. (2006) also showed that reduced corn yields in response to added P may occur in mineral

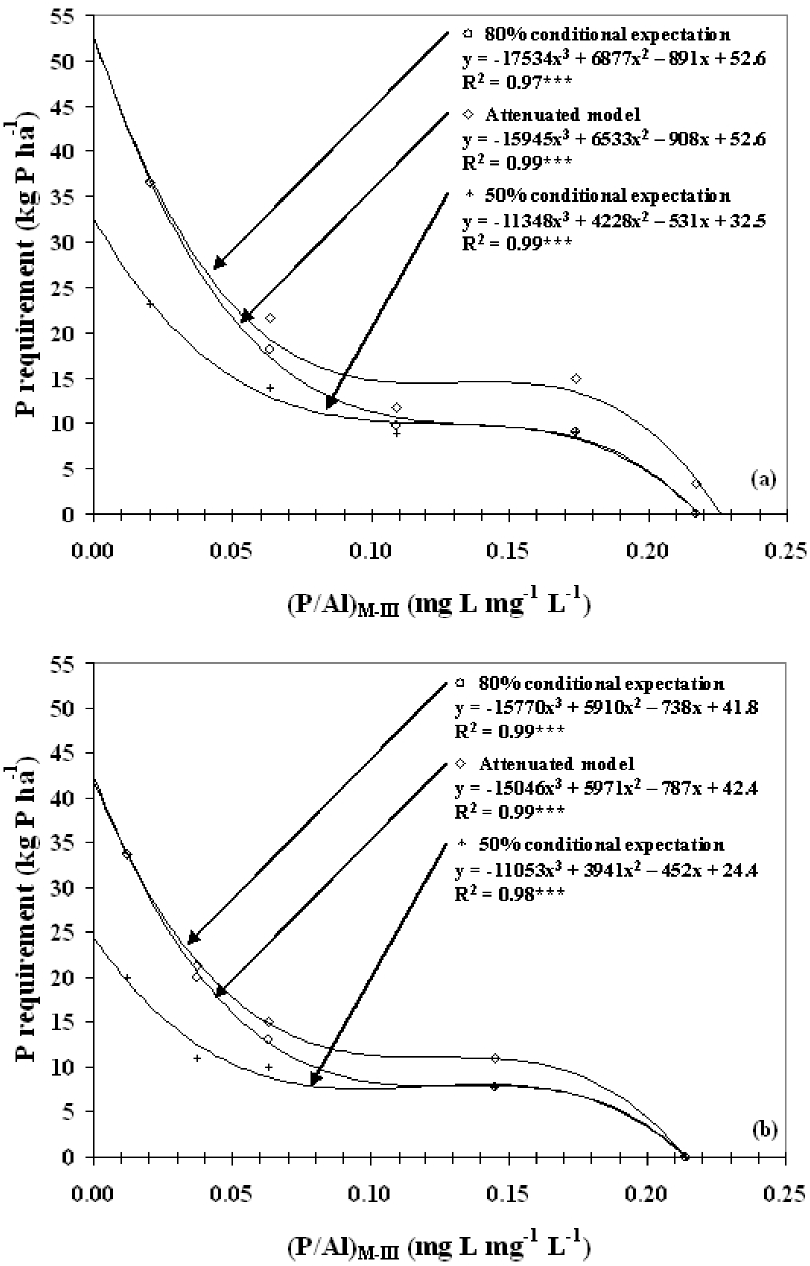

Fig. 3. Agri-environmental P requirement models for corn using the $(P/Al)_{M\text{-}III}$ ratio for (a) ≤ 300 g clay kg^{-1} and (b) > 300 g clay kg^{-1} soils.

soils of northeast USA, especially in soils with $(P/Al)_{M\text{-}III}$ ratios > 0.08. The power of corn response to added P in the Heckman et al. study (2006) was computed to be only 0.084 across 26 sites with $(P/Al)_{M\text{-}III}$ ratios > 0.08.

Site 5 presented a peculiar situation with a P requirement exceeding predicted P across the three P requirement models despite an extremely high $(P/Al)_{M\text{-}III}$ ratio of 0.239. The soil showed a high C content outside model range (Table 1). McKeague (1967) found that organo-metallic complexes accounted for a significant proportion of amorphous forms of Fe and Al in some Canadian soils. According to Levesque and Schnitzer (1967), the more Fe and Al are complexed by fulvic acids, the more phosphate can complexes sorb until maximum P incorporation is attained. Hence, the maximum saturation factor for total sorption for Quebec mineral soils ($\alpha_m = 0.51$) (Pellerin et al. 2006) may not apply to high C soils. More research is needed to establish the relationship between maximum saturation factor for total sorption and either the C content or the proportion of pyrophosphate-extractable Al and Fe in the soil. Also a $(P/[Al + Fe])_{M\text{-}III}$ molar ratio expression could be considered not only for soils receiving high amounts of metal-rich biosolids (Sims et al. 2002) but also for soils testing higher in organic matter and metal-HS complexes.

Table 5. Description of the 17 sites used to validate the P requirement models

Site	Location	Hybrid	CTU	Rainfall[z]	CTU[z]	Soil series[y]	pH	Sand	Clay	C	$P_{M\text{-}III}$	$Al_{M\text{-}III}$	$Fe_{M\text{-}III}$	$(P/Al)_{M\text{-}III}$
				mm				(g kg^{-1})			(mg kg^{-1})			(mg L mg^{-1} L^{-1})
						2002								
1	St-Léonard d'Aston	Pioneer 39A26	2450	457	2844	St-Sylvère, HFP	6.2	780	72	16	210	1170	379	0.180
2	Nicolet	Dekalb 29–95	2450	397	2800	Sorel, HFP	6.6	787	82	21	122	851	372	0.144
3	St-Sylvère	Dekalb 221	2250	395	2780	St-Aimé, O.HG	5.2	582	112	39	148	829	715	0.179
4	Sherrington	NK 2555 Bt	2700	663	2928	St-Jude, HFP	6.4	608	166	16	128	439	617	0.291
5	St-Louis-de-Gonzague	Pioneer 38P05	2850	496	3220	Ste-Barbe, R.HG	6.3	87	173	108	157	655	527	0.239
6	Sherrington	Dekalb 42–71	2850	712	2928	St-Mathieu, MB	7.0	411	191	25	69	717	296	0.096
7	St-Louis-de-Gonzague	Pioneer 37H27	3000	499	3280	St-Urbain, O.HG	6.0	102	392	19	57	811	386	0.070
8	St-Louis-de-Gonzague	Pioneer 39D82	2625	450	3188	Ste-Rosalie, O.HG	6.4	87	514	17	45	749	387	0.060
						2003								
9	St-Léonard d'Aston	Pioneer 39A26	2450	237	2782	St-Sylvère, HFP	4.5	451	100	29	37	2156	200	0.017
10	St-Valentin	NK 3030 Bt	2850	334	3024	St-Valentin, MB	5.5	600	133	11	30	515	341	0.057
11	St-Mathias	Pioneer 38G17	2500	385	2998	St-Jude, HFP	5.4	441	153	14	21	806	303	0.025
12	Nicolet	Codisem 250	2500	237	2782	La Baie, R.HG	5.8	130	167	23	31	556	465	0.056
13	St-Blaise	Pioneer 27M3	2775	328	3011	St-Blaise, O.HG	5.5	379	180	19	22	471	216	0.046
14	Mont St-Grégoire	Pioneer 27M3	2775	334	3024	St-Jude, HFP	4.7	294	222	13	35	636	367	0.056
15	St-Louis-Gonzague	NK 3030 Bt	2850	505	3346	St-Urbain, O.HG	6.1	256	377	18	35	369	243	0.095
16	St-Louis-Gonzague	Pioneer 39D82	2625	505	3346	Ste-Rosalie, O.HG	6.2	349	440	25	22	322	239	0.067
						2004								
17	St-Louis-Gonzague	Pioneer 39D82	2625	457	2888	Ste-Rosalie, O.HG	6.6	128	424	35	112	1371	145	0.082

[z] Cumulative value between seeding and harvest dates.

[y] HFP: humo-ferric podzol; O.HG: orthic humic gleysol; R.HG: regosolic humic gleysol; MB: melanic brunisol.

Table 6. Effects of banded fertilizer NP on corn yield and comparison of the computed economic P rate with the P addition recommended by the proposed models

		Treatment			Polynomial contrast		Computed	P requirement model			Closest model
		0	8.7	17.4	linear	quadratic	economic	Conditional expectation			vs.
		(kg P ha^{-1})									
Site	$(P/Al)_{M\text{-}III}$	Yield			F value		P rate	80%	Attenuated	50%	optimum P
	(mg L mg^{-1} L^{-1})	(Mg ha^{-1})					(kg P ha^{-1})				
					2002 (EMS[z] = 0.64; CV[y] = 8.1%)						
1	0.180	10.2	10.0	10.1	0.0NS	0.4NS	0	13	8	8	50%
2	0.144	10.5	8.6	8.6	13.9**	8,1**	0	15	10	10	50%
3	0.179	10.7	9.8	8.9	3.5†	0.0NS	0	13	8	8	50%
4	0.291	10.7	10.0	10.0	1.8NS	1.1NS	0	0	0	0	50%
5	0.239	11.3	11.9	11.1	0.1NS	4.3*	15	0	0	0	none
6	0.096	9.5	9.1	9.7	1.1NS	1.2NS	0	15	12	10	50%
7	0.070	9.6	9.4	9.5	0.0NS	0.0NS	0	14	11	8	50%[x]
8	0.060	8.4	9.0	8.9	0.9NS	1.2NS	0	15	13	9	50%[x]
					2003 (EMS[z] = 1.13; CV[y] = 9.8%)						
9	0.017	8.8	8.6	8.8	0.1NS	0.0NS	0	39	39	25	50%
10	0.057	12.7	13.7	13.2	0.6NS	1.6NS	0	21	19	14	50%
11	0.025	8.7	11.1	10.9	10.8**	11.8**	12	34	34	22	50%
12	0.056	11.6	12.0	10.2	0.5NS	2.4NS	0	21	19	14	50%
13	0.046	11.0	10.5	9.7	1.2NS	3.5†	0	24	23	16	50%
14	0.056	10.4	10.8	10.6	1.8NS	0.2NS	0	21	19	14	50%
15	0.095	13.8	13.3	13.3	0.5NS	0.5NS	0	12	9	8	50%[x]
16	0.067	12.1	9.0	9.7	0.0NS	3.8*	0	14	12	8	50%[x]
					2004 (EMS[z] = 0.27; CV[y] = 4.6%)						
17	0.082	11.3	11.4	11.3	0.0NS	0.2NS	0	12	10	8	50%[x]

[z] EMS, error mean square.

[y] CV = coefficient of variation ($100\sqrt{EMS}/\bar{x}$).

[x] > 300 g clay kg^{-1} soils.

†, *, ** Significant at $P < 0.10$, $P < 0.05$, and $P < 0.01$, respectively.

CONCLUSION

Soil fertility grouping, crop response models, and the $(P/Al)_{M\text{-}III}$ ratio were combined to improve P requirement models for corn and soybean productions in acid to near-neutral soils in Quebec. Compared with $P_{M\text{-}III}$ alone, the $(P/Al)_{M\text{-}III}$ ratio improved soil fertility classification for sites where corn was non-responsive to added P. Soil fertility classification differed between two textural groups ($\leq$ 300 g clay kg^{-1} and > 300 g clay kg^{-1}) showing contrasting agronomic and environmental thresholds. There were lower fertilizer P requirements in > 300 g clay kg^{-1} compared with $\leq$ 300 g clay kg^{-1} soils when the $(P/Al)_{M\text{-}III}$ ratio was similar. Agri-environmental P requirement models using the $(P/Al)_{M\text{-}III}$ ratio were built for the two textural groups using 50 or 80% conditional expectations of reaching economic yield. An attenuated model was simulated to reduce agronomic risk in low-fertility soils and limit environmental risk of applying fertilizer P in high to extremely high-fertility levels. Models showed that corn can be fertilized at P rates lower than P removal even at a relatively low $(P/Al)_{M\text{-}III}$ ratio with no yield loss. Soybean appeared to be even less responsive to both STP and added P compared with corn. The $(P/Al)_{M\text{-}III}$ ratio proved to be reliable criteria for building agri-environmental P recommendation models for sustainable corn and soybean production. However, a more complete model should document hybrid × fertilizer P interaction and relate P requirement to C content in future research.

ACKNOWLEDGEMENTS

We acknowledge the financial support of the Natural Science and Engineering Research Council of Canada (NSERC) (OG #2254), the Fonds pour la Formation de Chercheurs et de l'Aide à la Recherche (FCAR), RBF Technologies Inc., La Coopérative Fédérée de Québec and the Conseil de Recherches en Pêche et Agroalimentaire du Québec (CORPAQ).

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