Phosphorus concentrations in subsurface water as influenced by cropping systems and fertilizer sources

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Carefoot, J. P. and Whalen, J. K. 2003. **Phosphorus concentrations in subsurface water as influenced by cropping systems and fertilizer sources**. Can. J. Soil Sci. **83**: 203–212. Over-fertilization of agricultural soils with P has been linked to water pollution, and it is becoming apparent that subsurface P losses can be substantial. The silty-loam Gleysol chosen for this study contained 146 mg Mehlich-3 P kg^{-1}, which exceeds the critical limit (66 mg Mehlich-3 P kg^{-1}) for Québec. Equal quantities of fertilizer P (45 kg P ha^{-1}) were applied from inorganic (triple superphosphate) and organic (composted cattle manure) sources to corn-corn and corn-soybean rotations. We evaluated crop production, the Mehlich-3 P and degree of soil P saturation levels, and the P concentration in subsurface water. Crop yields were unaffected by the fertilizer source, and only 31 to 67% of the P applied over a 2-yr period was exported, suggesting that the P fertilizer rate, chosen to match the P requirements of the corn crop, was excessive. After 2 yr, surface (0 to 15 cm) soils contained 149 to 199 mg Mehlich-3 P kg^{-1} and the Mehlich-3 (P/Al) saturation ratio (DSPS_{M3}) ranged from 0.10 to 0.14. Subsurface water from piezometers installed to a 60-cm depth contained between 0.3 and 1.7 mg total P L^{-1}, and particulate P was the dominant P form at most sampling dates. Mehlich-3 P was positively correlated with dissolved reactive P, whereas the DSPS_{M3} was positively correlated with the total P and particulate P concentrations in subsurface water. We conclude that these soil test parameters could be useful indicators of subsurface P losses from Québec soils.

Key words: Soil test P, degree of soil P saturation, composted cattle manure, triple superphosphate, P leaching

Carefoot, J. P. et Whalen, J. K. 2003. **La concentration de phosphore lixivié du sol influencé par les cultures et les fertilisants**. Can. J. Soil Sci. **83**: 203–212. Il existe un lien évident entre la sur-fertilisation des sols agricoles en phosphore (P) et la pollution des eaux. Le Gleysol limoneau choisi pour cette etude contiennait 146 mg kg^{-1} du P selon la méthode Mehlich-3 (Mehlich-3 P), excédant ainsi la limite critique (66 mg Mehlich-3 P kg^{-1}) du Québec. Les quantités égaux d'engrais phosphorique (45 kg P ha^{-1}) ont été appliqué en forme inorganique (superphosphate triple) et organique (fumier de bétail composté) sur les cultures en rotation maïs-maïs et maïs-soya. Nous avons evalué la récolte des cultures, la quantité du Mehlich-3 P, le degré de saturation du sol en P (DSSP), et la concentration du P dans l'eau sous-terrain. Les récoltes ont été nullement affecté par la source de fertilisant. Seulement 31 à 67% du P appliqué sur un period du deux ans a été exporté, ceci nous laissons à croire que la taux de fertilisation du P, recommendait au Québec, est excessif. Après deux ans, le sols du surface (0 à 15 cm) contiennait 149 à 199 mg Mehlich-3 P kg^{-1} puis la ratio du saturation en P (P/Al) selon la méthode Mehlich-3 (DSSP_{M3}) a été entre 0.10 et 0.14. L'eau collectait d'un profondeur de 60 cm avec l'utilisation d'un pieometre contiennait entre 0.3 et 1.7 mg P totale L^{-1}. Le P en particules était la forme dominant du P totale la plupart du temps. Il y avait des correlations positif entre le Mehlich-3 P et le P reactif desolute dans l'eau, le DSSP_{M3} et le P totale dans l'eau, et le DSSP_{M3} et le P en particules dans l'eau. Ces testes du sol pourraient être des indicateurs utile des pertes du P des sols québecois.

Mots clés: Test de sol en P, le degré de saturation du sol en P, fumier de bétail composté, superphosphate triple, P lixivié

Agricultural intensification in North America in the past 30 yr has decoupled animal and plant production systems and led to nutrient surpluses, particularly in regions where livestock operations are concentrated. Soils that are over fertilized with P from manure and other agricultural residues, relative to crop requirements, pose a threat to water quality. Transport of P from agricultural soils to surface waters has been linked to eutrophication of lakes and estuaries because as little as 20 to 30 mg P L^{-1} in surface runoff can stimulate phytoplankton production (Daniel et al. 1998; Broesch et al. 2001).

The two major pathways for P transport from agricultural soils to waterways are through surface processes (e.g., erosion and runoff) and subsurface processes (e.g., leaching). The movement of agricultural P via surface processes is well studied and related to factors such as soil chemical and mineralogical properties, **soil test P** (**STP**) levels, agricultural management, landscape position and climate (Sharpley et al. 1996; Leclerc et al. 2000; Sims et al. 2000). It is becoming apparent that substantial quantities of P are transported through subsurface processes, particularly in organic soils, coarse-textured soils, and soils that have been over fertilized with P relative to crop requirements (Sims et al. 1998). The movement of agricultural P can occur through matrix flow and preferential flow, and preferential flow may be the most important pathway for transporting P to agricultural drains (Gächter et al. 1998; Simard et al. 2000). In Quebec, total P losses from poorly drained clay soils through tile drainage may range from 0.01 to 1.17 mg P L^{-1} or higher (Beauchemin et al. 1998; Simard et al. 2000).

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Particulate P (> 0.45 µm) tends to be the dominant form of P transported to tile drains, perhaps because most of the dissolved P (< 0.45 µm) is adsorbed by the soil matrix; however, the quantity of P leached is affected by soil texture, tillage and cropping practices, and rainfall events (Sims et al. 1998; Simard et al. 2000).

There is a growing need to devise methods of predicting subsurface P losses that account for preferential flow pathways and other soil properties that affect P sorption-desorption and leaching through the soil profile. Soil test P has been proposed as an indicator of P leaching because the quantity of total P leached increases rapidly above a STP level referred to as the "change point". Heckrath et al. (1995) found that concentrations in tile drains were less than 0.3 mg total P L^{-1} when STP was less than 60 mg Olson-P kg^{-1}, but increased to more than 2.5 mg total P L^{-1} when soils contained between 60 and 100 mg Olson-P kg^{-1}. They considered 60 mg Olson-P kg^{-1} to be the "change point" where leachate P concentrations increased rapidly per unit increase in STP. Subsequent studies have detected change points between STP (Olson-P, Mehlich-3 P) and P in subsurface drainage (Hesketh and Brookes 2000; McDowell and Sharpley 2001a; Maguire and Sims 2002).

The **degree of soil P saturation** (**DSPS**) has also been suggested as an indicator of subsurface P losses because it measures the proportion of P sorption sites in a soil that are saturated. Leinweber et al. (1999) found that total P concentrations in lysimeters under 20 field sites in Germany were correlated with the DSPS, measured as the ratio of acid ammonium oxalate-extractable P to oxalate-extractable Al and Fe. Other researchers have shown that the potential for P leaching increases greatly when the DSPS, based on oxalate-extractable P, Al and Fe, exceeds 25% (Maguire et al. 2001; McDowell and Sharpley 2001b). In Quebec, the DSPS method based on the ratio of Mehlich-3 extractable P to Mehlich-3 extractable Al has been adopted for acid soils with less than 6 g kg^{-1} of oxalate-extractable Al (Beauchemin and Simard 1999; Khiari et al. 2000). Maguire and Sims (2002) found that dissolved reactive P leached from intact soil cores related better to the DSPS [Mehlich-3 extractable P/(Mehlich-3 extractable Al + Mehlich-3 extractable Fe)] than STP values. In Delaware, soils with a DSPS >0.11 are considered to have above-optimum levels of P, and those with a DSPS >0.15 may require remedial action to reduce the potential for nonpoint source P pollution by runoff and leaching (Sims et al. 2002). Knowledge of the STP and DSPS levels in agricultural fields, in addition to soil chemical and hydrological properties, may be used to protect or improve subsurface water quality.

Management practices have been adopted in many regions to reduce the quantity of P transported to waterways through overland flow. One strategy is to require that P fertilizer applications match crop P needs when STP levels exceed a critical limit. In Quebec, a critical level of 66 mg Mehlich-3 P kg^{-1} was established in 1999 (Ministère de l'Environnement du Québec 1999). Yet, the quantity of P transported via subsurface pathways may remain high, particularly if the site is fertilized with organic residues because organic P is sorbed less strongly than inorganic P and thus may be leached (Frossard et al. 1989; Simard et al. 1995; Zheng et al. 2001). The quantities of P leached through soil increase after manure applications; 1 yr after dairy manure was applied, between 0.03 and 3.18 mg total P L^{-1} was measured in leachates from intact soil cores (McDowell and Sharpley 2001b). Yet, it is difficult to know whether the downward migration of P in soils with a history of manure applications is due to the form of P applied or the quantity of P applied, since manure applications based on crop N requirements generally supply more P than required by crops.

In this study, we chose a soil that had, on average, 146 mg Mehlich-3 P kg^{-1}, which exceeds the critical limit for Québec. We applied an equal quantity of P to soils from inorganic P fertilizer (triple superphosphate), organic P fertilizers (composted cattle manure) or mixtures of the two fertilizers. Our working hypothesis was that subsurface P losses would increase as the proportion of P applied from the organic fertilizer source increased. The objective of this study was to test the effect of inorganic and organic P fertilizers on crop production, Mehlich-3 P and DSPS levels, and the concentration of P in subsurface water. We also report the effect of inorganic and organic fertilizers on soil mineral N pools and the concentrations of dissolved C and N in subsurface water.

MATERIALS AND METHODS

The study site was located on the Macdonald Research Farm, Ste. Anne de Bellevue, Quebec. Mean monthly temperature range from –10.3°C in January to 18.0°C in July, with mean annual precipitation of 940 mm (Environment Canada Atmospheric Environmental Branch, unpublished data). The soil, a Humic Gleysol (fine-silty, mixed, frigid Typic Endoaquent), contained a silt-loam layer (mean thickness 28 cm) underlain by sand (mean thickness 6 cm) and clay starting at depths below 34 cm, on average. The top 15 cm of the silty-loam layer contained 300 g kg^{-1} of sand, 540 g kg^{-1} of silt and 160 g kg^{-1} of clay with 15.4 g C kg^{-1}, 1.24 g N kg^{-1} and pH 6.1. From 1991 to 2000, when this study began, the site was a conventionally tilled for grain corn (*Zea mays* L.) production and the nutrients required were supplied in liquid hog manure, urea and triple superphosphate fertilizers. Selected soil properties (0- to 15-cm depth) in the spring of 2000, before the experiment began, are provided in Table 1.

Experimental Design

The site was disked on 2 May 2000 with a tandem disk prior to plot establishment, and laid out in a factorial (tillage × crop rotation) design. There were two tillage treatments (no-till or conventional tillage) and three crop rotations (corn/soybean, soybean/corn or continuous corn), for a total of six factorial treatments. The factorial main plots were 20 m by 24 m, and were arranged in a randomized complete block design with four blocks, for a total of 24 main plots. A 3-m-wide unplanted alley separated the main plots within a block and an 8-m-wide unplanted alley separated the blocks. After plot establishment, no additional tillage operations were done on the no-till plots, but conventional tilled plots were tilled with a tandem disk each spring before seeding and with a mouldboard plough each fall after harvest.

Table 1. Total and extractable nutrients in soils from the study site prior to plot establishment (May 2000). Values are the mean of 24 replicate determinations

Nutrient	Value
Total C (g kg^{-1})^z	15.4
Total N (g kg^{-1})^z	1.24
Total P (g kg^{-1})^y	0.92
NO_3-N (mg kg^{-1})^x	11.1
NH_4-N (mg kg^{-1})^x	2.4
P_{M3} (mg kg^{-1})^w	146
K_{M3} (mg kg^{-1})^w	214
Ca_{M3} (mg kg^{-1})^w	891
Mg_{M3} (mg kg^{-1})^w	158
Al_{M3} (mg kg^{-1})^w	1311

^{z}Carlo Erba Flash EA NC Soils Analyzer (Milan, Italy).
^{y}Hydrogen peroxide/sulfuric acid digests (Parkinson and Allen 1975).
^{x}2 M KCl extracts (Maynard and Kalra 1993).
^{w}Mehlich-3 extracts (Tran and Simard 1993).

Each 20-m by 24-m main plot was split into four strips (20 m by 6 m). Corn plots received the same amount of N (200 kg N ha^{-1}) and P (45 kg P ha^{-1}), but from different fertilizer sources (inorganic fertilizers, composted cattle manure). Soybean plots received the same amount of P (45 kg P ha^{-1}) from inorganic fertilizer and/or composted cattle manure. The inorganic fertilizers used were ammonium nitrate and triple-superphosphate. The composted cattle manure applied in the spring of 2000 and 2001 was obtained from Les Composts du Quebec (Saint Henri, Quebec). It contained, on a dry weight basis, an average of 401 g total C kg^{-1}, 20.7 g total N kg^{-1} (Carlo Erba Flash EA NC Soils Analyzer, Milan, Italy), 2.3 g total P kg^{-1} [H_2SO_4/H_2O_2 digestion (Parkinson and Allen 1975)] and 0.66 kg H_2O kg^{-1} (105°C for 48 h). Composted cattle manure was applied at rates of 0, 15, 30 and 45 Mg ha^{-1} (wet weight basis), which were equivalent to 0, 33, 66 and 100% of silage corn P removal (45 kg P ha^{-1}), based on Conseil des productions végétales du Québec (2000) guidelines. Composted cattle manure was incorporated prior to seeding the conventional tillage plots, but left on the surface of no-till plots. The balance of P required came from triple-superphosphate banded at seeding.

All plots were seeded with a John Deere 7100 Max Emerge seeder. Silage corn (*Zea mays* L. ‘Cargill 2610’) treated with Maxim and Captan was planted on 30 May 2000 and 17 May 2001, at a rate of 75 000 seeds ha^{-1}. Soybeans (*Glycine max* L. Merr. ‘Cargill A0868TR’) treated with Soy Select, were planted on 1 June 2000 and 18 May 2001, at a rate of 400 000 seeds ha^{-1}. Plots under corn production received 50 kg N ha^{-1} from NH_4NO_3 banded at seeding. Additional NH_4NO_3 was sidedressed at the four- to five-leaf stage (about 1 mo after seeding) based on the assumption that 25% of the N in composted cattle manure would be available for corn uptake during the growing season. We estimated that 15 Mg ha^{-1} (wet weight) of composted manure would provide 50 kg ha^{-1} of plant available N, 30 Mg ha^{-1} of composted manure would provide 100 kg N ha^{-1}, and 45 Mg ha^{-1} of composted manure would provide 150 kg N ha^{-1}. No NH_4NO_3 fertilizer was applied to soybeans.

Crop and Soil Analyses

Corn yields were determined by harvesting the grain and stover of 20 plants randomly selected from the center of each split plot. Soybean grain yield was determined by combining a swath 3 m wide by 20 m long in the center of each split plot. Grain and stover samples were then oven-dried (70°C) to calculate yield on a dry matter basis, finely ground (<1 mm mesh), digested [H_2SO_4/H_2O_2 digestion (Parkinson and Allen 1975)] and analyzed for total N [cadmium reduction-diazotization method on a Lachat Quik-Chem AE flow-injection autoanalyzer (Lachat Instruments, Milwaukee, WI)] and total P [molybdenum blue method (Murphy and Riley 1962)].

Soil samples were taken in the fall after harvest, but before fall tillage, at 0- to 15-cm, 15- to 30-cm, and 30- to 60-cm depths using a tractor-mounted soil auger. Soil samples for each depth were composites of two cores (7.5-cm diameter) removed from each split plot. Mineral N (NH_4-N and NO_3-N) concentrations were determined in 2 M KCl extracts of sieved (<2 mm mesh) field-moist soils from the 0- to 15-cm depth within 2 wk of collection (Maynard and Kalra 1993). Soils were then dried in a forced-air oven (60°C for 48 h), and finely ground (<2 mm mesh sieve). Soils were extracted with Mehlich-3 solution (1:10 soil:solution) after shaking for 5 min at 130 rpm (Mehlich 1984; Tran and Simard 1993). Phosphate concentrations in Mehlich-3 extracts were evaluated by the molybdenum blue reaction (Murphy and Riley 1962), and the Al concentration was analyzed by atomic absorption spectrometry. The concentrations of Mehlich-3 P and Mehlich-3 Al were used to calculate the degree of soil P saturation ($DSPS_{M3}$) in each soil depth (Eq. 1).

$$DSPS_{M3} = \text{Mehlich-3 P/Mehlich-3 Al} \qquad (1)$$

The $DSPS_{M3}$ satisfactorily predicts the P sorption capacity in the A and B horizons of neutral to slightly alkaline, gleyed soils from Quebec that contain < 6 g kg^{-1} of oxalate-extractable Al (Beauchemin and Simard 1999). Therefore, it should be suitable for our study because soils at the site (0 to 15 cm) contained 2.9 g kg^{-1} of oxalate-extractable Al.

Soil Water Collection and Analysis

Piezometers were installed in the 48 plots under conventional tillage to a depth of 60 cm in October 2000 and October 2001 after harvest and fall tillage operations and removed in April 2001 and May 2002 before spring field operations. The piezometers were galvanized aluminum tubes (71 cm long, 4.8 cm internal diameter) with two 0.25-cm holes located 9.5 cm from the sealed bottom. A soil core 5 cm in diameter was removed from the 0- to 60-cm layer of the soil profile with a tractor-mounted soil auger. After piezometers were inserted into each hole, the open end above the soil surface was capped. The diameter of the hole was the same as the outer diameter of the piezometer, ensuring that we achieved a snug installation and probably did not create conditions that would cause preferential flow around the piezometers, although the subsurface water collected in piezometers could have originated from matrix or preferential flow. A hand pump was used to indirectly transfer the water collected from the piezometers into acid-washed plastic containers, and water samples were stored at –20°C until analysis.

Subsurface water was collected four times between October 2000 and the end of April 2001 on 17 November 2000, 28 November 2000, 15 April 2001 and 23 April 2001. Water samples were also collected five times between October 2001 and the end of May 2002 on 8 November 2001, 2 December 2001, 9 December 2001, 15 April 2002 and 9 May 2002. We were unable to collect water samples from all piezometers at each sampling date because of lower-than-normal precipitation during the study period and variation in drainage across the field site. The data presented are from the six sampling dates when between 60 and 100 mL of water was collected from more than half of the piezometers ($n > 24$).

One-half of each water sample was filtered (<0.45 µm) and analyzed for molybdate reactive P and total P, total dissolved C, NO_3-N, and total N. Total P in unfiltered water samples was also determined. The concentrations of molybdate reactive P and total P [persulfate digests of filtered and unfiltered water samples (Williams et al. 1995)] were determined colorimetrically with the ammonium molybdate-ascorbic acid method (Murphy and Riley 1962) on a Lachat Quik-Chem AE flow-injection autoanalyzer (Lachat Instruments, Milwaukee, WI). The following P pools were differentiated (Eqs. 2–4):

$$\text{Dissolved reactive P (DRP)} = \text{molybdate reactive P (filtered samples)} \quad (2)$$

$$\text{Dissolved unreactive P (DUP)} = \text{total P (filtered samples)} - \text{DRP} \quad (3)$$

$$\text{Particulate P (PP)} = \text{total P (unfiltered samples)} - \text{total P (filtered samples)} \quad (4)$$

Total dissolved C (**TDC**) concentrations were measured by wet combustion with a Shimadzu TOC-V carbon analyzer (Shimadzu Corporation, Kyoto, Japan). The concentrations of NO_3-N and total N [persulfate digest of filtered water sample (Williams et al. 1995)] were determined colorimetrically using the cadmium reduction-diazotization method on a Lachat Quik-Chem AE flow-injection autoanalyzer (Lachat Instruments, Milwaukee, WI). **Dissolved organic N** (**DON**) was the difference between the NO_3-N concentration in the persulfate digest and the NO_3-N concentration in undigested water samples.

Statistical Methods

Results are presented for plots under conventional tillage only. Data were analyzed statistically as a randomized complete block model by two-factor analysis of variance (crop rotation, fertilizer source) using SAS software for Windows, version 8.02 (SAS Institute, Inc., Cary, NC). Soil and crop data were affected significantly ($P < 0.001$) by the crop rotation × fertilizer source interaction. Subsurface water data were not affected by crop rotation and generally not by the fertilizer source, but repeated measures analysis demonstrated significant ($P < 0.001$) variation between sampling dates. Means comparisons of significant effects were done with a LSD test at the 95% confidence level. Spearman correlation coefficients were used to analyze the relationships between the nutrient concentrations in subsurface water and soil properties. Data presented in tables and graphs are untransformed means (± standard errors).

RESULTS AND DISCUSSION

Crop Yield, Nutrient Uptake and Soil Nutrient Concentrations

Corn and soybean yields were 40 to 50% higher in 2000 than 2001 due to a prolonged drought (35 d without significant precipitation) in July and August of 2001 (Table 2; Environment Canada Atmospheric Environmental Branch, unpublished data). Soils amended with organic and inorganic fertilizers produced similar yields in both years (Table 2). More N and P were removed from the continuous corn system in the 2000 and 2001 growing seasons than from the corn-soybean rotation because more biomass was harvested in corn silage than from soybeans (Table 3). The cumulative N removal in the continuous corn system was between 70 and 84% of the cumulative amount of N applied (400 kg N ha^{-1}) during the 2000 and 2001 growing seasons. Therefore, our assumptions regarding N availability from composted manure and corn N fertilizer requirements were probably reasonable and there was likely sufficient N in all fertilizer treatments to support corn production. However, only 31 to 67% of the 90 kg P ha^{-1} applied during the 2000 and 2001 growing seasons was removed at harvest, indicating that P fertilizers were applied in excess of crop P requirements.

After corn harvest in 2001, soil mineral N concentrations were higher in plots amended with 0 and 15 Mg ha^{-1} composted manure than those receiving 45 Mg ha^{-1} composted manure (Table 3). These differences are probably related to the form of N fertilizer applied, as the 0 and 15 Mg ha^{-1} treatments under corn production received 200 kg N ha^{-1} yr^{-1} and 150 kg N ha^{-1} yr^{-1}, respectively, as NH_4NO_3. In contrast, the 45 Mg ha^{-1} treatment received only 50 kg N ha^{-1} yr^{-1} as NH_4NO_3, banded at seeding. Similar results were observed in soils under soybean production in 2001, but were not clearly related to N fertilization because we did not apply NH_4NO_3 to the soybeans. In soils under corn production, it appears that there is more N immobilization and/or N loss from soils that receive most of their N from organic than inorganic fertilizers.

The Mehlich-3 P concentrations in the 0- to 15-cm soil depth after harvest in 2001 ranged from 149 to 199 mg kg^{-1}, but no consistent trends with respect to crop rotations and fertilizer sources were observed (Table 3). The $DSPS_{M3}$ level in the 0- to 15-cm depth of soils at the field site was 0.11 when the experiment was established in the spring of 2000 (Table 1). Following harvest in 2001, the $DSPS_{M3}$ levels ranged from 0.10 to 0.14 in the 0- to 15-cm depth, from 0.08 to 0.12 in the 15- to 30-cm depth, and were less than 0.03 in the 30- to 60-cm depth (Fig. 1). The $DSPS_{M3}$ in the 0- to 15-cm depth tended to be lower in soils under the soy-

Table 2. Crop yield (dry matter basis) in conventionally tilled soils in 2000 and 2001. Values are the mean (± standard error) of four (soybean) and eight (corn) replicate plots

Crop	Compost rate (Mg ha^{-1})	Yield (Mg ha^{-1}) 2000	2001
Corn	0^z	14.4 ± 0.6	8.7 ± 0.8
	15	14.0 ± 0.9	8.6 ± 0.7
	30	14.6 ± 0.4	7.3 ± 0.9
	45	14.0 ± 0.4	8.5 ± 0.8
Soybean	0	2.8 ± 0.1	1.7 ± 0.1
	15	2.5 ± 0.1	1.5 ± 0.2
	30	2.6 ± 0.1	1.3 ± 0.1
	45	2.5 ± 0.2	1.6 ± 0.1

^{z}All plots received 200 kg N ha^{-1} and 45 kg P ha^{-1} from composted manure, NH_4NO_3 and triple superphosphate fertilizers.

Table 3. Crop nutrient uptake and plant-available N and P in the 0- to 15-cm layer of conventionally tilled soils after harvest, 2001. The phase of the crop rotation grown in 2001 is indicated in bold. Crop N and Crop P are the cumulative N and P removed through harvests in 2000 and 2001

Crop rotation	Compost rate (Mg ha^{-1})	Crop N (kg ha^{-1})	Crop P (kg ha^{-1})	Mineral N (mg kg^{-1})	Mehlich-3 P (mg kg^{-1})
Corn-**Corn**	0	337*a*	60*a*	10.2*ab*	157*bc*
Corn-**Corn**	15	283*b*	49*b*	10.8*ab*	160*bc*
Corn-**Corn**	30	279*b*	51*ab*	8.1*bc*	178*ab*
Corn-**Corn**	45	317*ab*	58*ab*	4.1*cd*	199*a*
Soy-**Corn**	0	205*c*	28*d*	21.8*a*	182*a*
Soy-**Corn**	15	231*c*	33c*d*	16.9*a*	180*ab*
Soy-**Corn**	30	209*c*	29*d*	6.8bc	175*ab*
Soy-**Corn**	45	234*c*	34c*d*	3.7c*d*	166*bc*
Corn-**Soy**	0	202*c*	34c*d*	5.4b*c*	158*bc*
Corn-**Soy**	15	225*c*	39*c*	10.7*ab*	149*c*
Corn-**Soy**	30	204*c*	34*cd*	4.9*bc*	192*a*
Corn-**Soy**	45	227*c*	38*c*	2.3*d*	157*bc*
LSD ($P < 0.05$)		39	8	2.3	25

a–d Means within a column followed by the same letter are not significantly different ($P < 0.05$, LSD).

bean phase of the corn-soybean rotation than the other cropping systems, but no clear trends with respect to fertilizer sources were observed (Fig. 1). We expect that differences in Mehlich-3 P concentrations and the $DSPS_{M3}$ in soils under continuous corn and corn-soybean rotations will emerge if we continue to apply P fertilizers in excess of crop P requirements, but this needs to be confirmed. When equivalent amounts of P were applied to a fine-textured Gleysol for 9 yr, more labile P accumulated in soils amended with liquid dairy manure than triple superphosphate fertilizer (Zheng et al. 2001). Research is needed to determine whether continued annual applications of composted cattle manure would increase Mehlich-3 P and $DSPS_{M3}$ levels more than triple superphosphate fertilizer in the longer-term.

Soil Water Chemistry and Nutrient Concentrations

Subsurface water was collected in piezometers inserted to a 60-cm depth and contained from 14 to 39 mg L^{-1} of TDC, 6 to 26 mg L^{-1} of total N, and between 0.3 and 1.7 mg L^{-1} of total P (Fig. 2). Subsurface water collected on 28 November 2000 contained the highest concentrations of TDC, total N and total P (Fig. 2, Table 4). In contrast, subsurface water collected on 2 December 2001 contained the lowest concentrations of total P (Fig. 2, Table 4). Similar quantities of rain fell in the 3 d before these water samples were collected (24.6 mm of rain before 28 November 2000, 33.3 mm of rain before 2 December 2001), but soils were much drier in the autumn of 2000 than autumn 2001. The total precipitation in October and November 2000 was 88.3 mm, while 160.8 mm of precipitation fell in October and November 2001 (average precipitation for this period is 168.8 mm; Environment Canada Atmospheric Environmental Branch, unpublished data). Our findings are similar to those of Beauchemin et al. (1998), who found that total P concentrations in tile drainage were higher when drainage water was collected in autumn after heavy rainfall on dry soils than when it rained regularly and soils were wetter.

Although seasonal variation in the nutrient concentrations of subsurface water appear to be related to rainfall patterns (Brye et al. 2001; Simard et al. 2000), we did not find such a clear trend in this study. Rainfall affected our ability to collect subsurface water in the autumn and we found that most piezometers contained a water sample 3 d after an event that delivered at least 20 mm of precipitation. However, in the spring we collected subsurface water even when there had been little precipitation (0 to 7.5 mm) in the preceding three days (Environment Canada Atmospheric Environmental Branch, unpublished data). When soils are saturated in the spring due to snowmelt and subsurface recharge, we suggest that rainfall may not be the most important factor controlling the concentrations of TDC, total N and total P in subsurface water, but this remains to be confirmed.

Generally, there was no difference in the nutrient concentration of subsurface water that could be attributed to the types of fertilizer applied, with the exception of TDC concentrations on 17 April 2002 and 9 May 2002. There was significantly ($P < 0.05$, LSD) more TDC in the subsurface water from plots amended with 45 Mg ha^{-1} of composted manure than plots that received 0 and 30 Mg ha^{-1} of manure (17 April 2002) or 0, 15 and 30 Mg ha^{-1} of manure (9 May 2002) (Fig. 2). Other workers have shown that more dissolved C is leached from soils amended with animal manure than unamended soils (Bhogal and Shepherd 1997; Rochette and Gregorich 1998; Bol et al. 1999).

The TDC concentrations in subsurface water we report are consistent with literature values. Equilibrium-tension lysimeters installed 1.4 m below chisel-plowed and no-tillage corn agroecosystems typically contain between 15 and 60 mg TDC L^{-1} (Byre et al. 2001). The TDC concentration in subsurface water was correlated with NO_3-N, DRP and DUP concentrations (Fig. 3), but not to PP or DON concentrations (data not shown). The positive correlations observed between TDC and NO_3-N, DRP and DUP suggest that similar factors affect the leaching of these nutrients through the soil profile. Although the TDC concentrations were higher in subsurface water from soils amended with 45 Mg ha^{-1} y^{-1} of composted manure than the other fertilizer

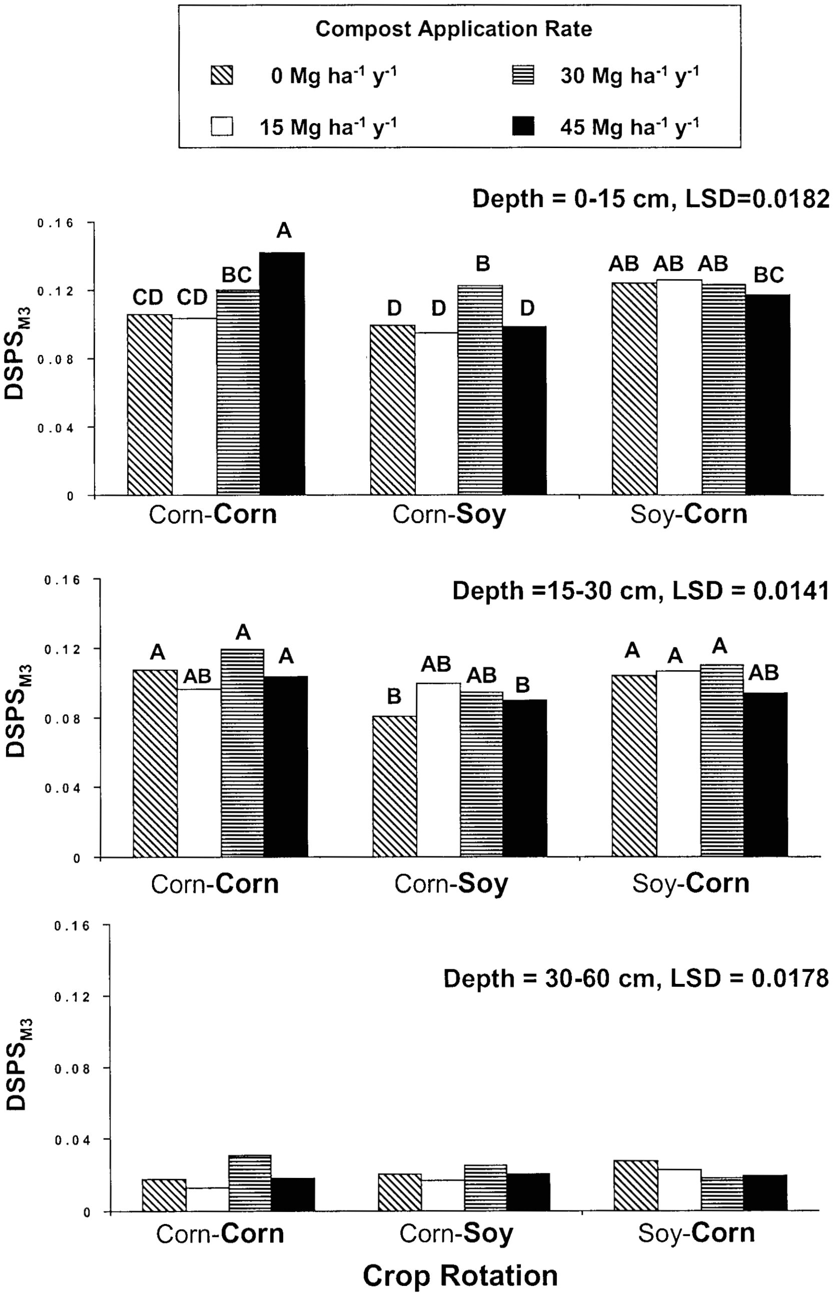

Fig. 1. The degree of soil P saturation ($DSPS_{M3}$), based on the Mehlich–3 P/Mehlich-3 Al saturation ratio, in soils amended with inorganic and organic fertilizers after harvest, 2001. Bars with different letters are significantly different ($P < 0.05$, LSD). The phase of the crop rotation grown in 2001 is indicated in bold.

treatments by the spring of 2002, the concentrations of NO_3-N, DRP and DUP in subsurface water were not affected by the fertilizer treatments. Further study is needed to determine whether the concentrations of dissolved C, N and P in subsurface waters are related to agricultural practices or to other factors, such as soil hydrology.

Nitrate was the major form of N collected in subsurface water at all sampling dates (Table 4). In corn production systems, mean NO_3-N concentrations in drainage discharge may range from 4 to 43 mg NO_3-N L^{-1} (Milburn and Richards 1994; Jaynes et al. 2001; Elmi et al. 2002), which is consistent with the NO_3-N concentrations we found in subsurface water. At some sampling dates, the average NO_3-N concentrations in subsurface water exceed the Canadian drinking water standard of 10 mg NO_3-N L^{-1} (Health and Welfare Canada 1996). The total N, DON and NO_3-N concentrations in subsurface water during the period between harvest and spring field operations were not correlated with the NO_3-N or mineral N concentrations in soil (0 to 15 cm) after harvest (Table 5). It is not clear from this

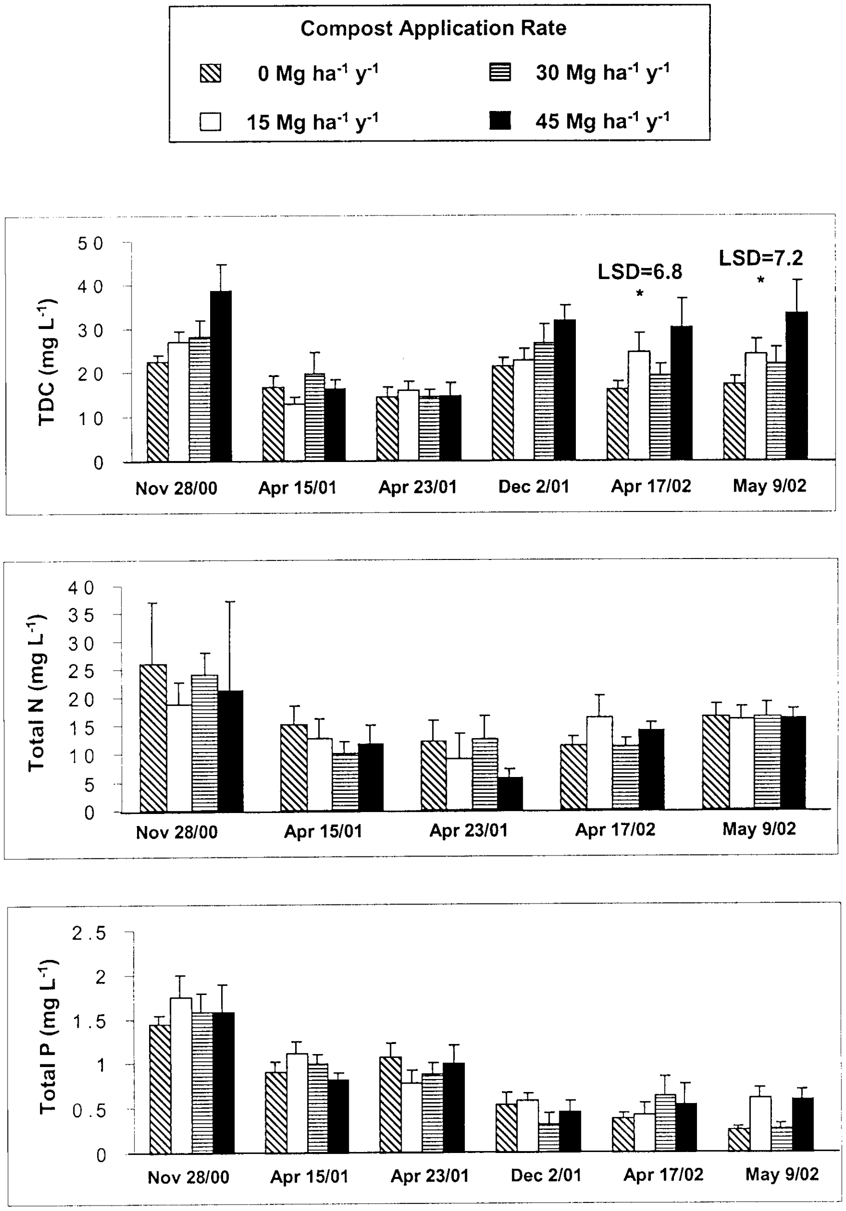

Fig. 2. Concentrations of total dissolved C (TDC), total N and total P in subsurface water from piezometers installed at a 60-cm depth in conventionally tilled soils. Data were pooled among crop rotations. The sampling dates when TDC concentrations varied significantly ($P < 0.05$, LSD) among fertilizer treatments are indicated with an asterisk.

study how crop rotations and fertilizer N sources (inorganic, organic) affected N concentrations in subsurface water, and additional monitoring is needed to determine if certain agricultural practices pose a greater risk to groundwater pollution with NO_3-N than others.

The total P concentrations in subsurface water collected during the study period are within the range of 0.01 to 1.17 mg total P L^{-1} in tile drains from 27 sites in Quebec reported by Simard et al. (2000). The total P concentration in subsurface water from our site exceeded the Quebec provincial surface water quality standard of 0.03 mg total P L^{-1} at all sampling dates (Ministere de l'Environnement du Quebec 2000). Our findings indicate that the quantities of P leached below the root zone in annually cropped, conventionally tilled soils are above those required to stimulate eutrophication. Gächter et al. (1998) estimated that more than half of the soluble reactive P draining into surface waters was leached from soils, contributing to the eutrophication of Lake Sempach, Switzerland. Therefore, subsurface P transport must be considered in models aimed at predicting the risk of water contamination with P from agricultural soils.

Particulate P was the dominant form of P collected in subsurface water at most sampling dates (Table 4). The forms of P collected in tile drainage are related to anecent soil

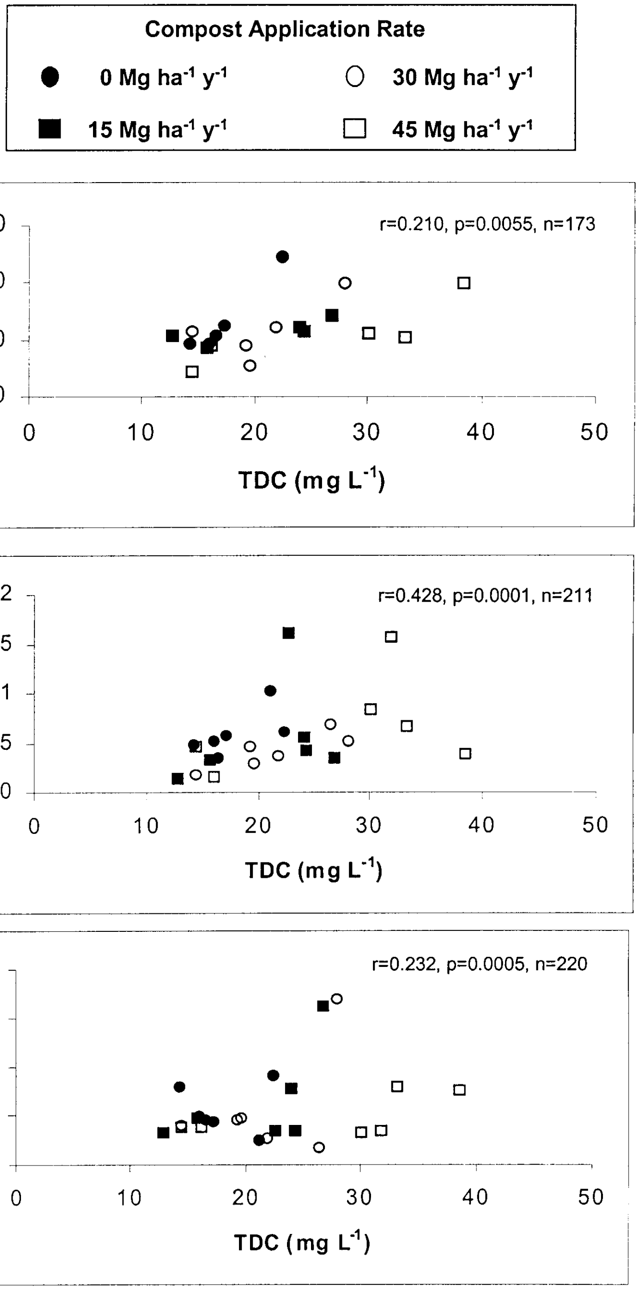

Fig. 3. Spearman correlation coefficients (*r*) between total dissolved C (TDC), N and P concentrations in subsurface water from piezometers installed at a 60-cm depth in conventionally tilled soils. DRP is dissolved reactive P and DUP is dissolved unreactive P. Values presented are the mean nutrient concentrations in subsurface water from each fertilizer treatment at six sampling dates between November 2000 and May 2002.

moisture and rainfall events, and PP concentrations are typically higher in tile drainage experiencing poststorm flow conditions (heavy rainfall following a dry period) than base flow conditions (Beauchemin et al. 1998; Simard et al. 2000). We found that PP was between 58 and 89% of the total P pool in subsurface water samples collected in a poststorm period (e.g., 28 November 2000) and in the spring following snowmelt (Table 4). It is clear that reducing the PP concentration in subsurface water would significantly lower the quantity of P leached through the soil profile, and further research is needed to determine the mechanisms governing PP transport through soils.

The narrow range of Mehlich-3 P and $DSPS_{M3}$ values in our soils made it difficult to determine relationships, such as the "change point", between P concentrations in soil and subsurface water. Other workers have studied soils with a wider range of STP values (Heckrath et al. 1995; Leinweber et al. 1999; Maguire and Sims 2002; Sims et al. 2002) or

Table 4. Mean concentrations of N and P compounds collected from piezometers installed at a 60-cm depth in conventionally tilled soils. Data were pooled among crop rotations and fertilizer sources. Total N and total P values are means (± standard errors)

Sampling date	Total N (mg L^{-1})	NO_3-N (mg L^{-1})	DON (mg L^{-1})	Total P (mg L^{-1})	DRP (mg L^{-1})	DUP (mg L^{-1})	PP (mg L^{-1})
28 Nov. 2000	20.3 ± 3.2	18.9*a*[y]	1.4*b*	1.03 ± 0.11	0.045*bc*	0.25*a*	0.73*a*
15 Apr. 2001	12.0 ± 1.5	8.8*b*	3.2*a*	0.88 ± 0.05	0.023*a*	0.08*bc*	0.78*a*
23 Apr. 2001	9.4 ± 1.7	8.3*b*	1.1*b*	0.69 ± 0.08	0.036*bc*	0.10*bc*	0.55*b*
2 Dec. 2001	ND[z]	ND	ND	0.27 ± 0.06	0.120*a*	0.05*c*	0.10*d*
17 Apr. 2002	12.7 ± 1.1	10.1*b*	2.6*a*	0.44 ± 0.08	0.055*b*	0.08*bc*	0.30*c*
9 May 2002	15.5 ± 1.1	11.8*b*	3.7*a*	0.40 ± 0.05	0.056*b*	0.11*b*	0.23*cd*
LSD ($P < 0.05$)		3.7	1.1		0.02	0.05	0.15

[z] ND = not determined.

a–d Means within a column followed by the same letter are not significantly different ($P < 0.05$, LSD).

Table 5. Spearman correlation coefficients (*r*) between soil nutrient concentrations after harvest and nutrient concentrations in subsurface water between harvest and spring field operations. Data are from the period November 2000 to May 2002 (*n* = 175 for N in subsurface water, *n* = 287 for P in subsurface water)

Nutrient concentration in subsurface water	Nutrient concentration in soil			
	Mineral N	NO_3-N	Mehlich-3 P	$DSPS_{M3}$
Total N	0.019	0.038	–	–
NO_3-N	0.002	–0.002	–	–
DON	0.045	0.038	–	–
Total P	–	–	0.089	0.273***
DRP	–	–	0.150*	0.105
DUP	–	–	0.039	0.069
PP	–	–	0.049	0.165**

*, **, *** Significant at $P = 0.05$, $P = 0.01$ and $P = 0.001$, respectively.

added P fertilizer to increase the STP concentrations (McDowell and Sharpley 2001b). Routine soil testing in Québec evaluates Mehlich-3 P and $DSPS_{M3}$ in surface soils (0- to 15-cm depth), which is why we looked for relationships between these parameters and the P concentration in subsurface water. The DRP concentration in subsurface water was positively correlated with the Mehlich-3 P concentration in soil (0 to 15 cm) after harvest, whereas total P and PP concentrations in subsurface water were positively correlated to the $DSPS_{M3}$ level in soil (0 to 15 cm) after harvest (Table 5). The correlation between DRP and Mehlich-3 P concentrations implies that the Mehlich-3 P test could indicate how much soluble P moves through the soil profile. Yet, total P and PP concentrations in subsurface water were better correlated with the $DSPS_{M3}$ level, which may indicate that the P content of particles transported in subsurface flow increases with increasing $DSPS_{M3}$ levels. We also found that total P and PP concentrations in subsurface water were positively correlated with the Mehlich-3 (P/[Al + Fe]) saturation ratio, but the correlation coefficients (*r*) were lower for this saturation ratio than the Mehlich-3 (P/Al) saturation ratio ($DSPS_{M3}$) we used (data not shown).

Other workers have found relationships between Mehlich-3 P and the concentration of DRP leached from intact soil columns (McDowell and Sharpley 2001b), but the DRP in leachates from intact soil cores was more strongly related to the Mehlich-3 (P/[Al + Fe]) saturation ratio ($r^2 = 0.87$) than the Mehlich-3 P concentration ($r^2 = 0.58$) (Maguire and Sims 2002; Sims et al. 2002). Total P concentrations in lysimeters permanently installed 1.25 m below coarse-textured soils was correlated better with the DSPS than Olson-P (Leinweber et al. 1999). Our results suggest the quantities and forms of P leached in a silty-loam Gleysol are related to the Mehlich-3 P and $DSPS_{M3}$ levels in the 0 to 15 cm depth. Additional study on soils with a wider range of STP and DSPS values is needed to confirm these relationships and develop models of subsurface P loss for soils in Québec.

CONCLUSIONS

Organic and inorganic fertilizers were applied at agronomic rates to a conventionally tilled silty-loam Gleysol under corn and soybean production for 2 yr. Between 70 and 84% of the N applied (200 kg N ha^{-1} y^{-1}) during this period was exported in corn silage, but only 31 to 67% of the P applied was removed in continuous corn and corn-soybean rotations, suggesting that the P fertilizer rate (45 kg P ha^{-1} yr^{-1}), chosen to match the P requirements of the corn crop, was excessive. Surface (0 to 15 cm) soils contained 149 to 199 mg Mehlich-3 P kg^{-1} and the $DSPS_{M3}$ levels ranged from 0.10 to 0.14 after harvest in 2001. Subsurface water was collected from piezometers installed to a 60-cm depth from November 2000 to April 2001, and from November 2001 to May 2002. Subsurface water contained 14 to 39 mg TDC L^{-1}, 6 to 26 mg total N L^{-1} and 0.3 to 1.7 mg total P L^{-1}. Nitrate and PP were the dominant forms of N and P in subsurface water at most sampling dates. The N and P concentration in subsurface water often exceeded water quality standards, but were not affected by the crop rotation or type of fertilizer applied. The Mehlich-3 P concentrations in soil following harvest was correlated with the DRP concentration, whereas the $DSPS_{M3}$ level was correlated with the total P and PP concentration in subsurface water. We conclude that these soil test parameters could be useful indicators of subsurface P losses from Québec soils.

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