Agricultural Practices Influence Dissolved Nutrients Leaching through Intact Soil Cores

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ABSTRACT

Nitrogen and P leaching from agricultural land to ground water poses a threat to water quality, but it may be possible to control dissolved nutrient leaching by choosing appropriate management practices. The objective of this study was to evaluate the effects of agricultural practices on dissolved N and dissolved P leaching from topsoil to subsurface soil after crop harvest. Intact soil cores and small disturbed soil columns were collected from a factorial (tillage × crop × fertilizer source) field experiment, 3 yr after the treatments were established. Soils were leached with synthetic rainwater in the laboratory and nutrient loads (kg ha^{-1}) were calculated. Dissolved N and dissolved P loads were not affected by tillage and were similar following corn (*Zea mays* L.) (in a continuous corn rotation) and soybean [*Glycine Max* (L.) Merr.] (in a soybean/corn rotation) production. Soils receiving inorganic fertilizer had a 70% greater nitrate (NO_3–N) load and 48% less dissolved reactive P than soils receiving organic fertilizer, suggesting that fertilizing soils with a combination of inorganic and organic fertilizers might be a good way to reduce both NO_3–N and dissolved reactive P transport to water systems. The NO_3–N load increased as the soil NO_3–N concentration increased ($R^2 = 0.36$) while the dissolved reactive P load was positively related to the soil Mehlich-3 P concentration ($R^2 = 0.50$) and soil P saturation ratio (M3-PSR) ($R^2 = 0.55$). These results suggest that the leaching of dissolved N and dissolved P compounds is influenced more by the type of fertilizer applied than tillage or cropping practices.

The transport of N and P from agricultural soils to ground water through leaching is of environmental concern and a potential risk to human health (Gaynor and Findlay, 1995; Owens et al., 2000; Zhao et al., 2001). Most of the N is leached as NO_3–N, which does not absorb to soil particles and is therefore more likely to be transported to subsurface tile drainage than in surface runoff (Owens et al., 2000; Zhao et al., 2001). Reports linking nitrate concentrations in drinking water to infant methemoglobinemia have led to a drinking water standard of 10 mg NO_3–N L^{-1} in many countries, including Canada (Health and Welfare Canada, 1996). Until recently, P leaching was seldom considered a significant pathway for transporting agricultural P to surface waters because it was believed that most soils had a considerable P adsorption capacity. However, Heckrath et al. (1995) reported significant export of P in agricultural drainage, with between 66 and 86% of the total P load in the form of dissolved reactive P. Phosphates can cause eutrophication in freshwater waterways and as little as 20 to 30 mg P L^{-1} can stimulate phytoplankton production (Daniel et al., 1998). Consequently, a limit of 0.10 mg ortho-P L^{-1} in the ground water at the level of the mean high water table was set in the Netherlands (Breeuwsma et al., 1995). Agricultural practices such as tillage, cropping systems, and fertilizer applications influence soil nutrient concentrations and drainage rates, leading us to believe that it may be possible to control NO_3–N and dissolved reactive P leaching from agricultural soils by choosing appropriate management practices.

Tillage has a two-fold effect on nutrient leaching: first, on soil nutrient concentrations and second, on water flow patterns. In general, tillage is expected to hasten decomposition of residues, resulting in more N mineralization and nitrification. Thus, more NO_3–N loss is expected in plowed than no-till soils (Power et al., 2001). Kanwar and Baker (1993) found greater NO_3–N concentrations in the 1.5-m depth of plowed than no-till soils. Yet, Eisenhauer et al. (1993) found that greater percolation of water through no-till than plowed soils led to more NO_3–N movement in the soil profile. Other researchers have found no consistent effects of tillage on NO_3–N leaching (Kanwar et al., 1995; Lamb et al., 1998). Fewer studies have investigated how tillage affects P leaching, but Gaynor and Findlay (1995) reported that 3-yr average concentrations of dissolved reactive P in the tile drainage waters were 0.24 mg L^{-1} for conventional tillage, and 0.54 mg L^{-1} for zero tillage. Sharpley et al. (2001) suggested that no tillage reduces soil erosion; thus decreasing particulate P losses, but increases water infiltration, therefore increasing dissolved P losses. Conventional tillage destroys macropores (e.g., soil cracks, root channels, and earthworm burrows) (Hangen et al., 2002) and could reduce the dissolved P lost through leaching.

Dissolved N and dissolved P lost from cropping systems by leaching are probably influenced by the amount, timing and method of fertilizer application, the residual amount of N and P in soils, as well as the rate of N and P mineralization from decomposing crop residues. Kanwar et al. (1997) found that the NO_3–N concentration in drainage water was 31 to 63% less in corn–soybean rotations than continuous corn systems, probably due to the lower N fertilizer input in corn–soybean systems. Grant et al. (2002) proposed that NO_3–N leaching could be reduced by including soybeans in crop rotations because soybeans do not generally receive N fertilizer and may remove residual soil N or symbiotically fix N_2 to meet their N requirements. We are not aware of studies that have evaluated P leaching in corn and corn–soybean systems.

Another factor affecting nutrient leaching is the type of fertilizer applied. Maeda et al. (2003) reported that the NO_3–N leached from a sweet corn-cabbage (*Brassica*

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Abbreviations: CC, continuous corn; CPVQ, Conseil des Productions Vegetales du Quebec; C/S, corn–soybean rotation; CT, conventional till; IF, inorganic fertilizer; M3-PSR, Mehlich-3 soil P saturation ratio calculated as the molar ratio of Mehlich-3 P/(Al + Fe); NT, no till; OF, organic fertilizer; S/C, soybean–corn rotation.

oleracea L.) system was less in plots receiving swine compost than inorganic fertilizers (coated urea and ammonium) for the first 4 yr, but there was no difference between fertilizer sources by the seventh year of the study. A review by Kirchmann and Bergstrom (2001) indicated that NO_3–N leaching losses were similar in conventional and organic farming systems when the quantities of N applied were taken into account. The potential for NO_3–N loss through leaching can be predicted from the soil NO_3–N concentrations and water movement through the soil profile (Meisinger and Delgado, 2002).

For P leaching, there was no difference in the dissolved reactive P concentration of subsurface water in soils amended with cattle manure compost or triple superphosphate for 2 yr (Carefoot and Whalen, 2003). Elliott et al. (2002) reported more P leaching from triple superphosphate than chicken manure in soil with a low P sorption capacity at P rates of 56 and 224 kg P ha^{-1}; for the soil with a high P sorption capacity, no difference was found between triple superphosphate and chicken manure applied at 56 kg P ha^{-1} but a greater P load was emitted from soils receiving triple superphosphate at a rate of 224 kg P ha^{-1}. Differences in P leaching from inorganic and organic fertilizer sources may be related to soil properties and the P fertilizer rate applied. The potential for dissolved reactive P loss through leaching can be predicted using soil test P and soil P saturation values (McDowell and Sharpley, 2001a; Maguire and Sims, 2002; Sims et al., 2002).

In northern climates, a critical period for N and P leaching is over the winter, between harvest and spring planting, due to the lack of crop growth and greater water infiltration, especially after snowmelt in the spring. Thus, residual nutrients in the soil may be susceptible to transport, but it is not known whether certain combinations of tillage practices, crop rotations, and fertilizer sources may reduce the residual soil nutrient concentration and thus decrease NO_3–N and dissolved reactive P losses through leaching. In addition, little information exists on how management practices affect the transport of compounds such as dissolved organic N and dissolved organic P. In corn and corn–soybean systems, Carefoot and Whalen (2003) found that 7 to 27% of the total N in subsurface water was dissolved organic N and between 9 and 28% of the total P was dissolved organic P. Stevens and Wannop (1987) studied the composition of total soluble N in leachate from lysimeters and found that more than 90% was in the form of dissolved organic N within the organic horizons, but NO_3–N predominated in the deeper soil layers, suggesting that dissolved organic N was transformed to NO_3–N during percolation. Murphy et al. (2000) proposed that soluble organic N and dissolved organic N could be readily transformed into NO_3–N. Since dissolved organic N and dissolved organic P may possibly be transformed into NO_3–N and dissolved reactive P as they travel through the soil profile, it is necessary to determine how management practices affect their loss from soils through leaching.

The objectives of this study were: (i) to evaluate the effects of tillage, crops and fertilizer sources on the loads of NO_3–N, dissolved reactive P, dissolved organic N, and dissolved organic P leached from the 0- to 20-cm layer of a silt-loam soil collected after crop harvest, and (ii) to determine whether dissolved N and dissolved P loads in leachates were related to residual nutrient concentrations in the soil.

MATERIALS AND METHODS

Field Site

The field site was located on the Macdonald Research Farm, Ste. Anne de Bellevue, Quebec, Canada, approximately 3 km north of the St. Lawrence River (45°28′ N lat., 73°45′ W long., elevation 35.7 m). The ground water table is at about 2 m in August and rises to 30 cm in spring after snowmelt. Annual temperature at the nearby Dorval climate station (Dorval International Airport, Quebec, Canada) averages 6.1°C, with mean annual precipitation of 967 mm. The soil is a fine-silty, mixed, frigid Typic Endoaquent, containing 300 g kg^{-1} of sand, 540 g kg^{-1} of silt and 160 g kg^{-1} of clay with 15.4 g total C kg^{-1} and pH 6.1 in the 0- to 15-cm layer. Additional details were provided by Carefoot and Whalen (2003).

In May 2000, a factorial (tillage × crop rotation) experiment was established with two tillage treatments [no-till (NT) or conventional tillage (CT)] and three crop rotations [corn–soybean (C/S), S/C or continuous corn (CC); only one crop per year], for a total of six factorial treatments. The factorial plots were 20 by 24 m, and were arranged in a randomized complete block design with four blocks. No-till plots were directly seeded each spring, while conventional tilled plots were tilled with a tandem disk to 10 cm each spring before seeding and with a moldboard plow to 20 cm each fall after harvest.

Each 20 by 24-m plot was split into four strips (20 by 6 m) and four fertilizer treatments were applied randomly to the strips. All fertilizer treatments received the same amount of total P (45 kg P ha^{-1}), but from different fertilizer sources [inorganic fertilizer and/or organic fertilizer (composted cattle manure)]. The inorganic fertilizers used were ammonium nitrate and triple superphosphate. The organic fertilizer (composted cattle manure) applied in the spring of 2000, 2001, and 2002 was obtained from Les Composts du Quebec (Saint Henri, Quebec, Canada) and contained, on average, 20.7 g total N kg^{-1}, 2.3 g total P kg^{-1}, and 0.66 kg H_2O kg^{-1} (Whalen et al., 2003). Organic fertilizer 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 the P application rate (45 kg P ha^{-1}) recommended for silage corn production in Quebec [Conseil des productions vegetales du Quebec (CPVQ), 2000]. Organic fertilizer was incorporated into conventional tillage plots before seeding, but left on the surface of no-till plots. The balance of P required in each treatment came from triple superphosphate banded at seeding.

Silage corn (*Zea mays* L. 'Cargill 2610') and soybeans (*Glycine max* L. Merr. 'Cargill A0868TR') were planted in late May or early June each year from 2000 to 2002. Both crops received same amount of composted cattle manure. Plots under corn production received 50 kg N ha^{-1} from NH_4NO_3 banded at seeding. As much as 150 kg N ha^{-1} of NH_4NO_3 was side-dressed at the four- to five-leaf stage to provide 200 kg N ha^{-1} in total, based on the assumption that 25% of the N in organic fertilizer would be available for corn uptake during the growing season. Soybeans did not receive any inorganic N fertilizer but received N from the organic fertilizer.

Table 1. Description of experimental treatments used in this study. The phase of the crop rotation grown in 2002 is underscored.

Treatment†	Tillage system	Crop grown	Fertilizer applied
NT-CC-IF	no-till	corn–corn	inorganic‡
NT-CC-OF	no-till	corn–corn	organic§
NT-S/C-IF	no-till	soy–corn	inorganic
NT-S/C-OF	no-till	soy–corn	organic
CT-CC-IF	conventional tillage	corn–corn	inorganic
CT-CC-OF	conventional tillage	corn–corn	organic
CT-S/C-IF	conventional tillage	soy–corn	inorganic
CT-S/C-OF	conventional tillage	soy–corn	organic

† NT, no-till; CT, conventional till; CC, continuous corn (*Zea mays* L.); S/C, soybean (*Glycine max* L. Merr.)–corn; OF, organic fertilizer; IF, inorganic fertilizer.

‡ The inorganic treatment received 200 kg N ha^{-1} from NH_4NO_3 for corn production, and 45 kg P ha^{-1} from triple-superphosphate for corn and soybean.

§ The organic treatment supplied 150 kg N ha^{-1} and 45 kg P ha^{-1} from composted cattle manure for corn and soybean. Plots under corn production received at seeding 50 kg N ha^{-1} from NH_4NO_3.

Nutrient Leaching from Intact Soil Cores

Only eight treatments, including two tillage systems [no-till (NT) or conventional tillage (CT)], two crop rotations [S/C or CC] and two fertilizer treatments [all P from inorganic fertilizer (IF) or all P from composted cattle manure (OF)] were selected from the field experiment. Intact soil cores (three replicates per treatment) were taken from eight treatments at the study site in October 2002 after harvest, but before fall tillage (Table 1). Each intact soil core (10-cm diam., 20-cm depth) was collected adjacent to the crop row by hammering a PVC column into the ground. This size of soil core was chosen for its ease of handling and to minimize disturbance to the field experiment. Our intact soil cores are slightly smaller than the 15-cm diam. cores that were used by McDowell and Sharpley (2001a), Maguire and Sims (2002), and Chapman et al. (1997) for P leaching experiments. A depth of 20 cm was chosen to estimate the dissolved nutrient load that would be transported from the topsoil into subsurface soil, but it should be noted that these data couldn't be used to predict nutrient loading in ground water that may result from agricultural practices. Cores were carefully dug out of the ground, capped for transport to the laboratory and stored at 4°C. Duplicate soil samples (0- to 20-cm depth) were collected from each plot, composited and passed through a 2-mm mesh sieve, sealed in plastic bags and stored at 4°C until analysis. Sieved soil samples were used to assess soil characteristics in each plot. Bulk density for each plot was measured by collecting two samples using cylinders with 8.5-cm diam. and 7.7-cm height.

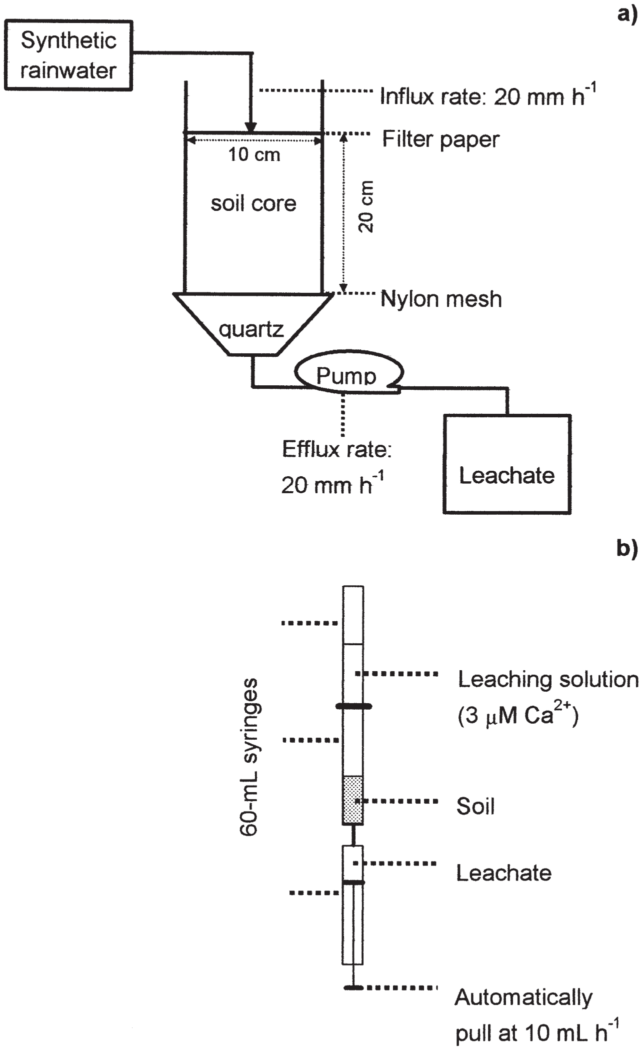

Fig. 1. Schematic diagram of leaching apparatus used in (a) the intact soil core study and (b) the disturbed small soil column study.

In the laboratory, the top and bottom surfaces of intact soil cores were vacuum cleaned to reopen any clogged pores. A nylon mesh with opening of approximately 25 μm was attached at the bottom (in comparison, soil macropores are >50 μm). A funnel containing pure crystal quartz (3 mm and less in diameter, acid-washed) was fitted to the bottom of core, and was sealed with silicon (Fig. 1a). Then, cores were placed in a rack and put into an incubator at 6°C, the mean annual temperature at the field site, to suppress biological interference during the leaching process. To avoid dispersion of the soil from influent droplets, filter paper (Whatman 2) was placed on the surface of soil. Synthetic rainwater was applied to the surface of soil core at the rate of 20 mm h^{-1}, the average efflux rate of the rainfall simulator (Bowman et al., 1994). The chemical composition of synthetic rainwater (Table 2) was based on rainfall from southern Quebec, Canada (Sirois et al., 2000). At same time, a peristaltic pump that had an efflux rate of 20 mm h^{-1}, was used to collect the leachate and also gave the soil core suction. The suction provided did not represent the water tension under field conditions (Fig. 1a). Each core was leached with 121 mm (950 mL) of synthetic rainwater twice a week for 4 wk (eight leaching events in total). After eight leaching events, each core had received 968 mm synthetic rainwater, which is equivalent to mean annual precipitation at the study site. It should be noted that the rate and duration of leaching do not reflect field conditions. Similar methods were used by Chapman et al. (1997) for P leaching (900 mL a week for 6 mo) and by McDowell and Sharpley (2001b) in a lysimeter study on P losses (20 mm h^{-1} for 1 h). The volume of leachate collected after each leaching event was recorded, and approximately 100 mL of leachate

Table 2. Chemical composition of the synthetic rainwater used for the intact soil core study.

Parameter	Value
SO_4^{2-}, mg L^{-1}	2.24
NO_3^-, mg L^{-1}	1.92
Cl^-, mg L^{-1}	0.13
Ca^{2+}, mg L^{-1}	0.12
NH_4^+, mg L^{-1}	0.34
Mg^{2+}, mg L^{-1}	0.02
Na^+, mg L^{-1}	0.04
K^+, mg L^{-1}	0.02
pH	4.22

was centrifuged, passed through a 0.45-μm membrane, and frozen until analysis.

Nutrient Leaching from Disturbed Small Soil Columns

Soil samples were collected from the same field plots as above in May 2003 before spring field operations (tillage, fertilization, and seeding). Five samples were collected from the 0- to 20-cm depth of each plot with a soil auger (2.5-cm diam.), composited, air-dried, and passed through a 2-mm mesh sieve. Thirty grams of each composite sample were placed into a 60-mL syringe with a polyethylene frit (2.7-cm diam. and 0.2-cm thickness, specifically used for this 60-mL syringe) (Supelco, Bellefonte, PA) at the bottom, and another frit was put on the surface of the soil (Fig. 1b). A leaching solution (1.5 μM $CaCl_2$ and 1.5 μM $CaSO_4$, pH 4.2 adjusted with HCl), which has the same Ca^{2+} concentration as the synthetic rainwater in Study 1, was used. The soil was saturated under vacuum to 80% pore volume with leaching solution, placed in the leaching apparatus (Centurion International Inc., Lincoln, NE; Fig. 1b), and put into a refrigerator at 6°C. After 24 h, the soil columns were leached with 30 mL of solution every day for 8 d (eight leaching events). During each leaching event, syringes were pulled at 10 mL h^{-1} for 3 h to collect leachate and then for another 3 h to aerate the soil column. All leachates were filtered through a 0.45-μm membrane and frozen until analysis. Thus, all nutrients in leachates are in dissolved forms.

Soil and Leachate Analysis

Soil NO_3–N and NH_4–N concentrations were determined in 2 M KCl extracts (Maynard and Kalra, 1993). We also determined the Mehlich-3 P, Al and Fe concentrations in soils (Mehlich, 1984). The NO_3–N and dissolved reactive P concentrations in leachates were determined, and a subsample of each leachate collected was oxidized with a potassium persulfate solution (Williams et al., 1995). The dissolved organic N concentration in leachates was the difference between the NO_3–N concentration in the oxidized sample and the mineral N (NH_4–N + NO_3–N) concentration in the unoxidized leachate, whereas the dissolved organic P concentration was the difference in dissolved reactive P between oxidized and unoxidized leachates.

The NO_3–N and NH_4–N concentrations in soil extracts and leachates were determined using the Cd reduction-diazotization and salicylate methods (Lachat Instruments, 2000), and P concentrations with the ammonium molybdate-ascorbic acid method (Murphy and Riley, 1962), using a Lachat Quik-Chem AE flow-injection autoanalyzer (Lachat Instruments, Milwaukee, WI). Mehlich-3 Al and Fe were analyzed by atomic absorption spectrometry (AAS). The dissolved organic C concentration in unoxidized leachates was measured by wet combustion with a Shimadzu TOC-V carbon analyzer (Shimadzu Corporation, Kyoto, Japan).

The Mehlich-3 soil P saturation ratio (M3-PSR) was calculated from Eq. [1]:

$$\text{M3-PSR} = \text{P}/(\text{Al} + \text{Fe}) \qquad [1]$$

where P, Al, and Fe are concentrations in Mehlich-3 soil extracts, expressed on a molar basis.

The nutrient load in leachates (X, in kg ha^{-1}) was calculated from Eq. [2]:

$$X = \left(\sum_{i=1}^{8} C_i V_i\right) \times \frac{A}{a} \qquad [2]$$

where i is the leaching event; C_i is the concentration of the leachate from the ith leaching event in kg L^{-1}; V_i is the volume of the leachate from the ith leaching event in L; A is the area of 1 ha in m^2 ha^{-1}; and a, in m^2, is the area of the surface of an intact soil core or the equivalent area of a disturbed soil column calculated as: {30 g/[bulk density (g cm^{-3}) × 20 cm]}× 10^{-4}.

Statistical Analyses

Contrast analyses between the key agricultural management practices, that is, tillage, crops and fertilizer sources, and means comparison (Duncan's multiple range test at $P < 0.1$ significance level) between treatments were performed with the SAS GLM procedure (SAS for Windows, Version 8.2). Regression analyses were conducted with the SAS REG procedure and regression lines were added to the graphs by using the function of add-trendline in tools of Microsoft Excel 98 software (Microsoft Inc., Remond, WA). Two intact soil cores, one from treatment NT–S/C–IF, another from treatment CT–S/C–OF, deteriorated during the leaching process. The statistical analyses and the results reported for the intact soil core study are based on the data collected only, that is, no estimation of missing values.

RESULTS AND DISCUSSION

In the intact soil core study, we found that the time needed to collect the same volume of leachate after applying a uniform amount of synthetic rainfall varied substantially among treatments (Table 3), leading to considerable variation in the P concentration between leaching events. Some cores leached slowly, and water ponded on the soil surface. The study with disturbed small soil columns was conducted to determine whether water ponding in intact soil cores affected the total P load (kg P ha^{-1}) estimated from the leaching study. We are not comparing the total N and total P loads from the intact soil cores and the disturbed small soil columns because soil samples for these studies were not collected at same time, but instead use this data to compare the dynamics of N and P leaching with these two methods and also to evaluate how agricultural practices affected the dissolved N and dissolved P loads in each study.

Nitrogen Concentration in Leachates

We chose one treatment (Fig. 2a,b) to demonstrate the change in N concentration after eight leaching events, since all treatments showed a similar trend. Both intact soil core and disturbed small soil column studies showed that NO_3–N and dissolved organic N concentrations declined exponentially over the eight leaching events (Fig. 2a,b). This indicates a similar pattern of N loss from topsoil with both leaching methods. However, the N concentration in leachates from disturbed soil columns was about three times less than that from intact soil cores. Soil samples for the disturbed column study were collected 7 mo after the intact soil cores. It is likely that some NO_3–N was lost from the topsoil at the field site over winter since N is not strongly absorbed to soil particles (Owens et al., 2000). The NO_3–N concentration in leachate from intact soil cores was greater than the drinking water limit of 10 mg NO_3–N L^{-1} (Health and Welfare Canada, 1996) after the first leaching event, but declined to 3.08 mg NO_3–N L^{-1} by the third leaching event (Fig. 2a).

Table 3. Leachate volumes collected after the application of 950 mL of synthetic rainfall, and the approximate time required to collect this volume.

	Replicate I			Replicate II			Replicate III		
Treatment†	1st event‡	2nd to 8th ave.§	Time	1st event‡	2nd to 8th ave.§	Time	1st event‡	2nd to 8th ave.§	Time
	mL		h	mL		h	mL		h
NT-CC-IF	643	903	8	725	918	8	594	925	8
NT-CC-OF	660	907	8	480	908	22	635	923	8
NT-S/C-IF	663	914	22	651	930	8	nd	nd	nd
NT-S/C-OF	690	914	56	751	917	22	751	897	56
CT-CC-IF	655	903	8	670	911	8	770	927	8
CT-CC-OF	648	921	22	700	898	8	600	924	8
CT-S/C-IF	680	899	32	632	904	8	724	922	22
CT-S/C-OF	520	893	32	nd¶	nd	nd	710	910	22

† NT, no-till; CT, conventional till; CC, continuous corn (*Zea mays* L.); S/C, soybean (*Glycine max* L. Merr.)–corn; OF, organic fertilizer; IF, inorganic fertilizer.

‡ Volumes of leachate in 1st leaching event varied and <950 mL of the added rainfall was collected during column equilibration.

§ Volumes of leachate collected from the 2nd to the 8th leaching event were consistent.

¶ Not determined because of column deterioration during the leaching process.

The NO_3–N load leached from intact soil cores (Table 4) was equivalent to between 10.5 and 16.5% of the N applied the previous spring at field site. Nitrogen leaching losses from grain production systems have been reported to range from 10 to 30% of the N applied (Meisinger and Delgado, 2002). The NO_3–N load was greater in soils receiving inorganic fertilizer than organic fertilizers (Table 4), presumably because the inorganic fertilizer treatment received more NH_4NO_3 fertilizer (200 kg N ha^{-1}) than the organic fertilizer treatment (50 kg N ha^{-1}) when corn was grown. Under soybean production, the N load was less in the organic fertilizer plots (treatment CT-S/C-OF, Table 4) than the plots that did not receive any N fertilizer (treatment CT-S/C-IF). It should be noted that the soil N concentration was less in organically fertilized soils under soybean production than those that did not receive N fertilizer, perhaps due to N immobilization or gaseous N losses during the growing season (Table 4). The NO_3–N load did not differ between fertilizer sources in the disturbed small soil column study (Table 4), but the soils for this study were collected 7 mo after those for the intact soil core study. It seems likely that NO_3–N was lost from soils at the study site between October 2002 and May 2003 through leaching or denitrification, but this remains to be confirmed.

Between 23 and 56% of the total N load was in the form of dissolved organic N in the intact soil core study, while from 46 to 57% of the total N load was dissolved organic N in the disturbed small soil column study (Table 4). In addition, there was a positive relationship between the dissolved organic C and dissolved organic N loads (Fig. 3a,b), suggesting they are transported together under field conditions. A similar relationship for dissolved organic C and dissolved organic N was reported by Qualls et al. (2002) in deciduous forests of the Appalachian Mountains. Dissolved organic C is considered to be a readily available substrate for soil microorganisms (Brye et al., 2001) and could stimulate dissolved organic N mineralization and nitrification in the soil profile, leading to an increase in the dissolved NO_3–N concentration with depth. Further work is required to determine what proportion of dissolved organic N is converted to NO_3–N as it leaches through the soil profile.

Phosphorus Concentration in Leachates

The concentrations of P, including dissolved reactive P and dissolved organic P, varied considerably among leaching events. Here, we chose treatment CT-CC-IF to demonstrate the variations in P concentration among the replicates and among leaching events (Fig. 4a,b). We could not find a suitable equation to describe the fluctuation of dissolved reactive P and dissolved organic P concentrations in leachate from intact soil cores (Fig. 4a), which was likely due to uneven contact between synthetic rainfall and the soil matrix. The dynamics of dis-

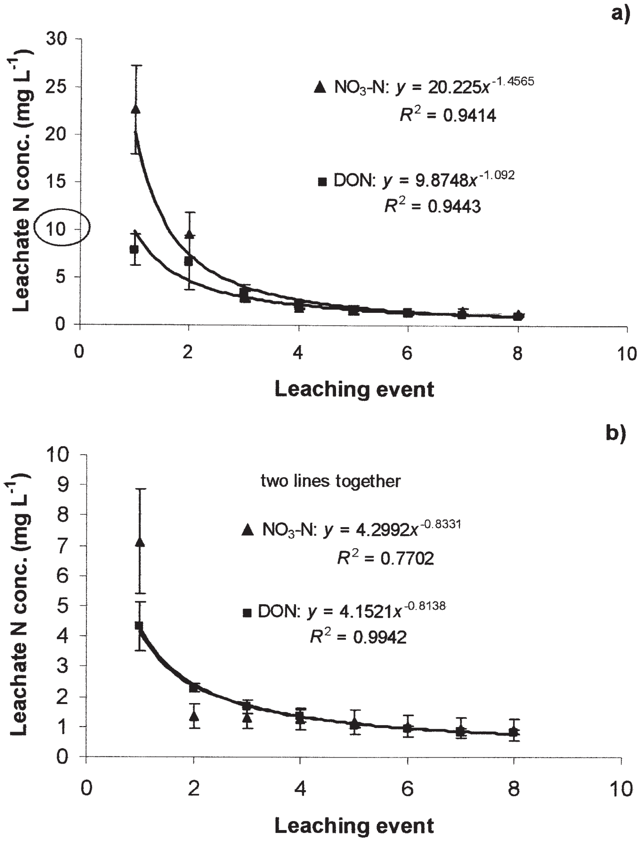

Fig. 2. Dissolved N [NO_3–N and dissolved organic N (DON)] concentrations in leachates from the treatment CT-CC-IF collected from (a) intact soil cores and (b) from disturbed small soil columns. The drinking water limit of 10 mg NO_3–N L^{-1} is circled.

Table 4. Nitrogen loads (kg ha^{-1}) as influenced by tillage, crop rotations, and fertilizer sources.

	Soil, mg kg^{-1}		Leachate, kg ha^{-1}			
Treatment†	NO_3–N	NH_4–N	NO_3–N	NH_4–N	DON§	DOC¶
			Intact soil core study			
NT-CC-IF	9.55 cd‡	1.59 a	32.9 ab	5.3 a	20.5 a	222 c
NT-CC-OF	8.05 cd	1.75 a	27.7 bc	14.0 a	31.1 a	411 a
NT-S/C-IF	18.56 ab	2.19 a	29.6 ab	7.8 a	22.1 a	192 c
NT-S/C-OF	11.65 bcd	1.93 a	20.3 c	5.0 a	23.5 a	244 bc
CT-CC-IF	20.80 a	2.08 a	43.4 ab	11.8 a	26.6 a	205 c
CT-CC-OF	6.67 d	1.82 a	21.0 c	5.2 a	33.1 a	365 ab
CT-S/C-IF	15.76 abc	2.33 a	44.9 a	7.7 a	33.4 a	193 c
CT-S/C-OF	6.08 d	1.99 a	18.8 c	1.4 a	25.3 a	262 bc
			Contrast (significance probability)			
NT vs CT			NS#	NS	NS	NS
CC vs SC			NS	NS	NS	0.0668
IF vs OF			0.0100	NS	NS	0.0146
			Disturbed small soil column study			
NT-CC-IF	2.43 bc	3.57 b	31.7 a	1.29 b	34.7 b	368 bc
NT-CC-OF	1.58 c	3.05 b	34.5 a	4.95 a	52.3 a	569 a
NT-S/C-IF	1.43 c	2.71 b	29.0 a	0.63 b	31.4 b	324 c
NT-S/C-OF	1.45 c	3.33 b	35.6 a	1.82 b	45.9 a	468 b
CT-CC-IF	5.35 a	6.44 a	39.1 a	1.83 b	34.9 b	361 bc
CT-CC-OF	3.60 b	3.15 b	33.2 a	1.89 b	45.7 a	445 b
CT-S/C-IF	3.44 b	3.68 b	39.0 a	0.80 b	36.4 b	390 bc
CT-S/C-OF	3.49 b	3.39 b	31.8 a	1.51 b	44.2 a	447 b
			Contrast (significance probability)			
NT vs CT			NS	NS	NS	NS
CC vs SC			NS	0.0099	NS	NS
IF vs OF			NS	0.0068	<0.0001	<0.0002

† NT, no-till; CT, conventional till; CC, continuous corn; S/C, soybean–corn; OF, organic fertilizer; IF, inorganic fertilizer.
‡ Values within a column followed by different letters are significantly different at the 0.1 level (Duncan's multiple range test) in each study.
§ Dissolved organic N.
¶ Dissolved organic C.
# Not significant ($P > 0.1$).

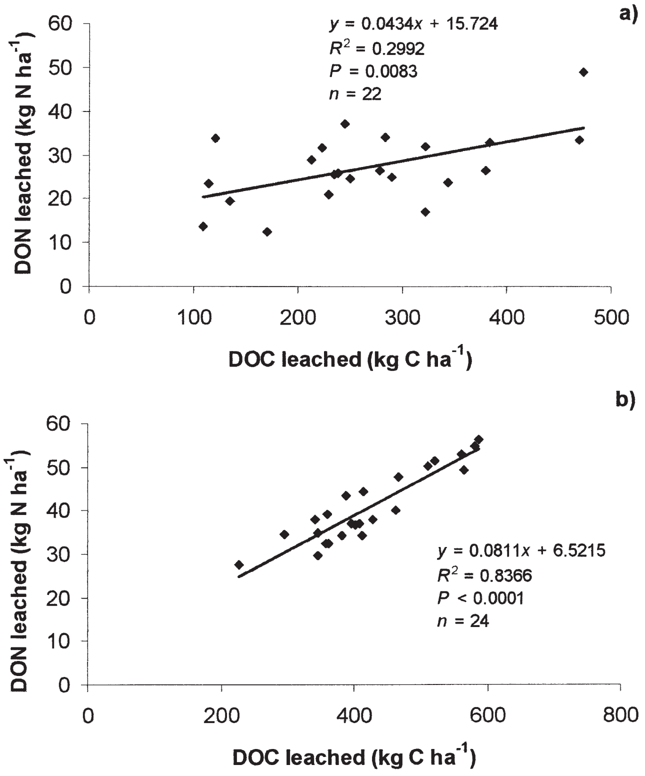

Fig. 3. Relationship between dissolved organic C (DOC) and dissolved organic N (DON) loads in leachates from (a) the intact soil cores and (b) the disturbed small soil columns.

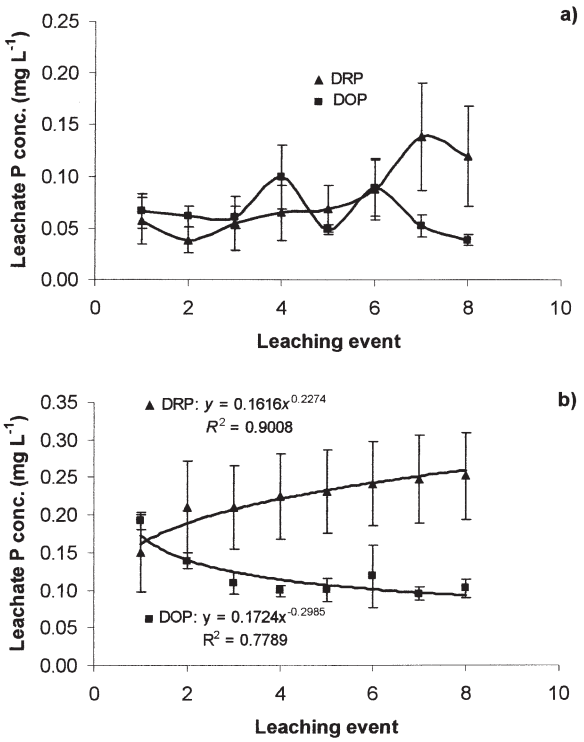

Fig. 4. Dissolved P [dissolved reactive P (DRP) and dissolved organic P (DOP)] concentrations in leachates from the treatment conventional till (CT)–continuous corn (CC)–inorganic fertilizer (IF) collected from (a) intact soil cores and (b) disturbed small soil columns.

Table 5. Phosphorus loads (kg ha^{-1}) as influenced by tillage, crop rotations and fertilizer sources.

	Mehlich-3 soil test		Leachate, kg P ha^{-1}	
Treatment†	P, mg kg^{-1}	M3-PSR§	DRP¶	DOP#
	Intact soil core study			
NT-CC-IF	133.6 ab‡	0.078 ab	0.77 bc	0.58 ab
NT-CC-OF	138.8 ab	0.084 ab	0.89 bc	0.88 ab
NT-S/C-IF	122.0 b	0.070 b	0.47 c	0.46 b
NT-S/C-OF	127.0 b	0.078 ab	3.72 a	1.46 a
CT-CC-IF	145.6 ab	0.083 ab	0.72 bc	0.58 ab
CT-CC-OF	156.5 ab	0.103 a	1.43 bc	1.14 ab
CT-S/C-IF	163.4 a	0.100 a	2.40 ab	1.15 ab
CT-S/C-OF	148.4 ab	0.095 ab	2.45 ab	1.13 ab
	Contrast (significance probability)			
NT vs CT			NS††	NS
CC vs SC			0.0008	0.0481
IF vs OF			0.0123	0.0216
	Disturbed small soil column study			
NT-CC-IF	152.7 ab	0.091 ab	7.1 b	2.71 b
NT-CC-OF	163.0 ab	0.099 ab	17.8 a	3.69 a
NT-S/C-IF	125.0 b	0.072 b	4.0 b	2.42 b
NT-S/C-OF	144.4 ab	0.087 ab	12.3 ab	2.61 b
CT-CC-IF	142.9 ab	0.082 ab	4.6 b	2.53 b
CT-CC-OF	156.4 ab	0.097 ab	8.8 ab	2.53 b
CT-S/C-IF	171.0 a	0.103 a	10.3 ab	2.60 b
CT-S/C-OF	170.3 ab	0.106 a	11.2 ab	2.53 b
	Contrast (significance probability)			
NT vs CT			NS	NS
CC vs SC			NS	NS
IF vs OF			0.0295	NS

† NT, no-till; CT, conventional till; CC, continuous corn (*Zea mays* L.); S/C, soybean (*Glycine max* L. Merr.)–corn; OF, organic fertilizer; IF, inorganic fertilizer.
‡ Values within a column followed by different letters are significantly different at the 0.1 level (Duncan's multiple range test) in each study.
§ Mehlich-3 soil phosphorus saturation level.
¶ Dissolved reactive P.
# Dissolved organic P.
†† Not significant ($P > 0.1$).

solved reactive P and dissolved organic P concentrations were different in the disturbed small soil column study, where we controlled the time that the leaching solution was in contact with the soil (Fig. 4b). The dissolved reactive P concentrations increased slightly through time in the disturbed small soil column study (Fig. 4b), indicating the continuous release of desorbable P with each subsequent leaching event. Other researchers have reported an exponential pattern of P desorption, with a phase of rapid P release from soil particles followed by a period of slower P desorption (Maguire et al., 2001).

The dissolved reactive P load was not affected by tillage in the intact and disturbed soil column studies (Table 5). More dissolved reactive P was leached from soils under a soybean–corn rotation than from soils under CC in intact soil core study, but there was no difference in disturbed small soil column study (Table 5). This finding is likely related to difficulties encountered with two replicates in treatment NT-S/C-OF (Table 5) that exhibited poor water infiltration and ponding at the soil surface, taking many more hours than other intact cores to produce an equivalent volume of leachate (Table 3). The dissolved reactive P concentrations in the leachates from these two intact soil cores were twice as great as the other intact soil core from the same treatment. Coincidently, the NO_3–N concentration was less from these two soil cores than the other intact soil core, and the NO_3–N load from this treatment was the least of any treatment (Table 4). This indicates that the rate of water movement through the soil profile influences the NO_3–N and dissolved reactive P loads in leachates. A possible explanation is that during water ponding, nitrate may be reduced to nitrite and then to N_2 or even N_2O, reducing the NO_3–N concentration in leachate; at same time, Fe^{+3} may be reduced to Fe^{+2}, releasing P from Fe-P compounds and leading to a greater dissolved reactive P concentration in leachate. This possibility needs to be studied further.

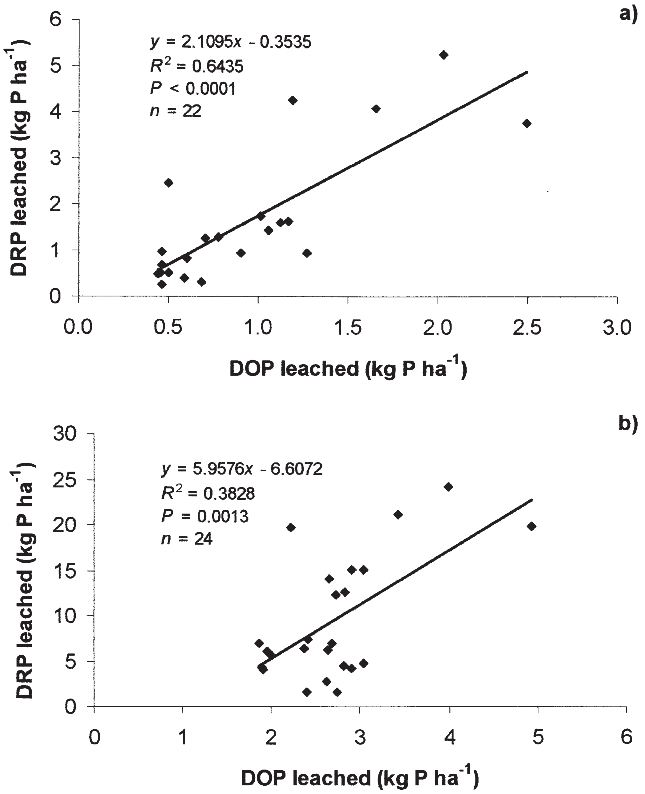

Fig. 5. Relationship between dissolved organic P (DOP) and dissolved reactive P (DRP) loads in leachates from (a) the intact soil cores and (b) the disturbed small soil columns.

The dissolved reactive P load in no-till soils under soybean production was significantly ($P < 0.05$) greater when soils were amended with organic fertilizer than inorganic fertilizer, suggesting that P mobility was affected by the type of fertilizer applied (Table 5). One explanation is that negatively charged organic molecules from organic fertilizer may compete with HPO_4^{2-} and $H_2PO_4^-$ for binding sites on Fe and Al oxides (Iyamuremye and Dick, 1996), thus leading to more dissolved reactive P leaching. If this is the case, then phosphates from triple superphosphate may have been retained more tightly by Fe and Al oxides and hence did not desorb and leach as readily.

The dissolved organic P load was positively related to the dissolved reactive P load in both intact soil core study (Fig. 5a) and disturbed small soil column study (Fig. 5b), which is similar to findings reported by Qualls et al. (2002) in a deciduous forest ecosystem. Between 32 and 50% of the total P load was in the form of

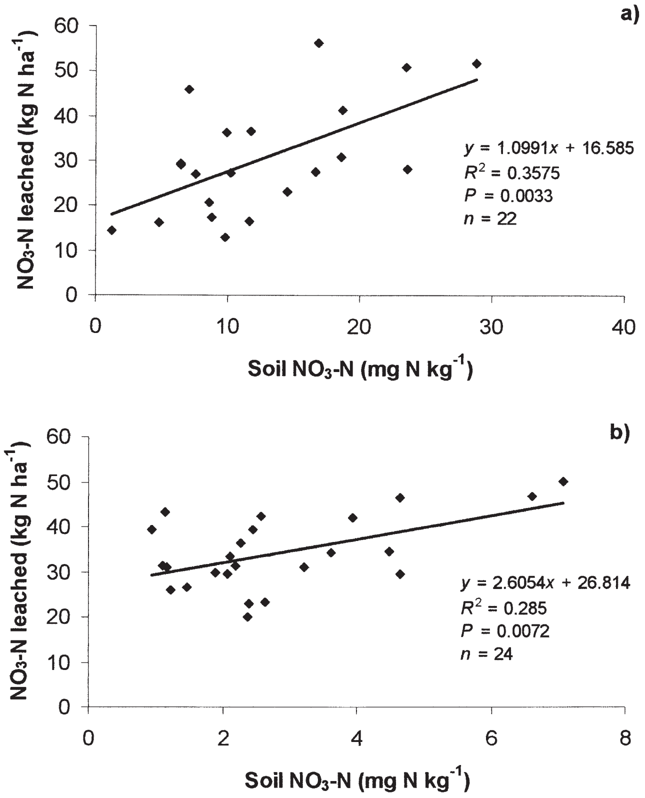

Fig. 6. Relationships between soil NO_3–N concentration and NO_3–N load in leachates from (a) the intact soil cores and (b) the disturbed small soil columns.

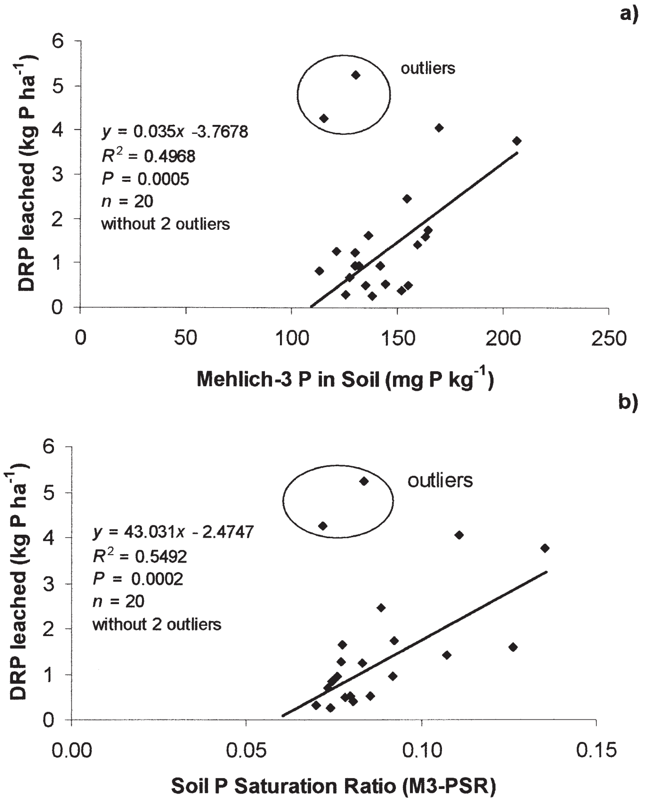

Fig. 7. Relationships between (a) the soil Mehlich-3 P concentration and dissolved reactive P (DRP) load in leachates, and (b) the soil Mehlich-3 P saturation ratio (M3-PSR) and dissolved reactive P (DRP) load in leachates. Leachates were collected from intact soil cores.

dissolved organic P in the intact soil core study and from 17 to 38% in disturbed small soil column study (Table 5). In an iron humus podzol, Ron Vaz et al. (1993) found dissolved organic P to be the most significant fraction in soil solution below the 10-cm soil depth on plots that received as much as 80 kg P ha^{-1} yr^{-1} as superphosphate, with dissolved organic P concentrations as great as 0.46 mg P L^{-1}. In a laboratory experiment, Lilienfein et al. (2004) demonstrated that competitive adsorption exists between dissolved organic P and orthophosphates, and soil had weaker adsorption strength and less adsorption capacity for dissolved organic P than for orthophosphate. In a corn agroecosystem receiving 300 kg P ha^{-1} yr^{-1} from cattle slurry, Chardon et al. (1997) reported that more than 70% of total P in leachates was in the dissolved organic P form. These results suggest that dissolved organic P is easily transported in the soil profile and that the dissolved organic P load may increase when organic fertilizers are applied.

Regulations limiting the P concentration in surface water are based on total P, including the U.S. Environmental Protection Agency standard of 0.05 mg total P L^{-1} for lakes (Sims et al., 1998) and Quebec limit of 0.03 mg total P L^{-1} for the surface water (Bobee et al., 1977). We are not aware of regulations on the P concentration in ground water except the 0.10 mg ortho-P L^{-1} limit that was set in the Netherlands (Breeuwsma et al., 1995; Sims et al., 1998). It may be advisable to base any future P limit for ground water on total P to account for both dissolved reactive P and dissolved organic P compounds contained in leachates.

Relationship between Soil Test Levels and N and P Leaching

The NO_3–N load in leachates was positively related to the soil NO_3–N concentration in both intact soil cores and disturbed small soil columns (Fig. 6), indicating that soil NO_3–N levels may be an indicator of NO_3–N leaching from topsoils to subsurface soils. Soil NO_3–N concentrations, as well as water infiltration rates, can be used to predict NO_3–N leaching losses and adjust management strategies to reduce N leaching (Minshew et al., 2002; Schaffer et al., 1991). The dissolved reactive P load in leachates was positively related to the Mehlich-3 P concentration and the M3-PSR in soils, if two outliers from the intact soil cores that leached slowly were not included (Fig. 7). When we leached disturbed small soil columns, we found positive linear relationships between the dissolved reactive P load and the soil test P values (Mehlich-3 P concentration and M3-PSR) (Fig. 8). These findings indicate that the contact time between water and soil, as well as the soil hydraulic conductivity, can affect our ability to accurately measure and predict P leaching from soils.

In an intact soil core study, McDowell and Sharpley (2001a) found that the dissolved reactive P concentration in leachates was stable with an increase in Mehlich-3

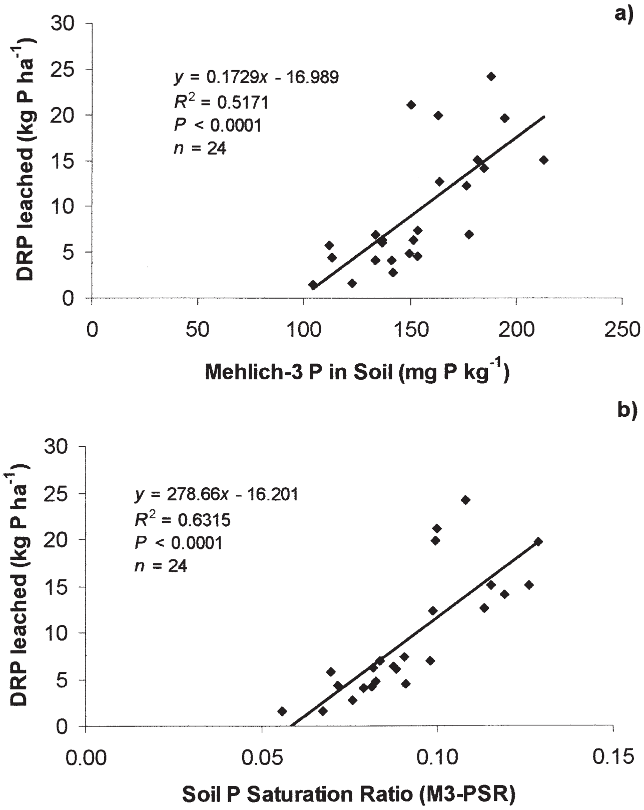

Fig. 8. Relationships between (a) the soil Mehlich-3 P concentration and dissolved reactive P (DRP) load in leachates, and (b) the soil Mehlich-3 P saturation ratio (M3-PSR) and dissolved reactive P (DRP) load in leachates. Leachates were collected from disturbed small soil columns.

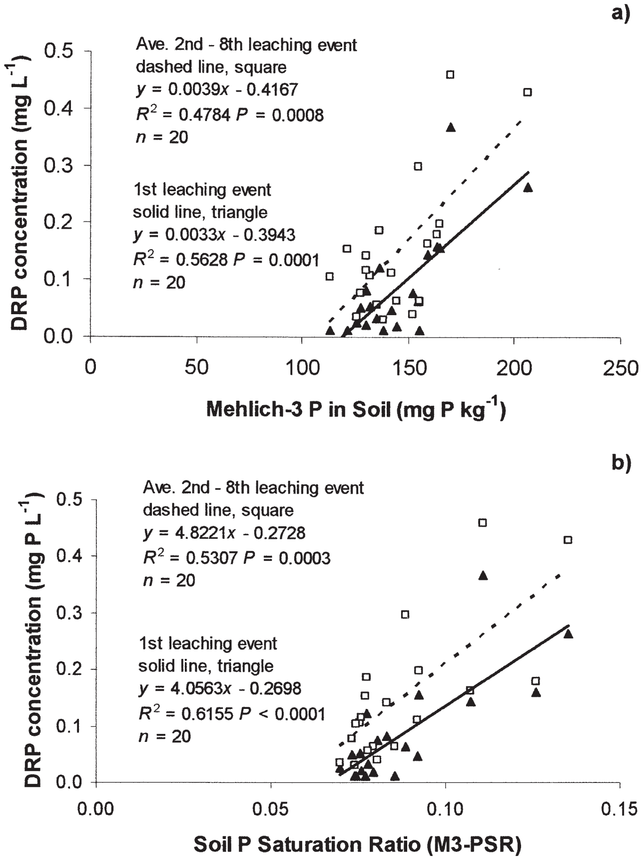

Fig. 9. Relationships between (a) the soil Mehlich-3 P concentration and dissolved reactive P (DRP) concentration in leachates and (b) the soil Mehlich-3 P saturation ratio (M3-PSR) and dissolved reactive P (DRP) concentration in leachates. Data were from the intact soil core study (n = 20, two outliers were not included in the regression analysis).

P concentrations between 11 to 193 mg P kg^{-1}, but increased linearly when Mehlich-3 P concentrations increased from 193 mg P kg^{-1} (change point) to 674 mg P kg^{-1} for two of four arable soils. Similarly, Maguire and Sims (2002) found a change point at 181 mg Mehlich-3 P kg^{-1} and at 0.2 M3-PSR using five soil series with soil test P concentrations between 16 to 890 mg Mehlich-3 P kg^{-1}. In our intact soil core study, soil test P concentrations ranged from 100.4 to 206.1 mg Mehlich-3 P kg^{-1} and from 0.061 to 0.135 M3-PSR; owing to the narrow range of soil test P concentrations, it was not possible to calculate a change point for dissolved reactive P at our site. The slopes of the regression lines relating dissolved reactive P and Mehlich-3 P concentrations were 0.0033 (first leaching event) and 0.0039 (average data from second to eighth leaching events) (Fig. 9a). These are less than the slopes of 0.009 to 0.0124 for regression lines above the change point reported by McDowell and Sharpley (2001a) and Maguire and Sims (2002). The slope of the line relating dissolved reactive P and M3-PSR in this study was between 4.06 and 4.82 (Fig. 9b), which is less than the slope of 28.44 for values above the change point reported by Maguire and Sims (2002). It is difficult to compare the slopes of lines relating dissolved reactive P in leachates to soil test P values with data generated from other studies because our soil test P values may have been less than or greater than the change point for this soil. We would need to collect and leach intact cores with a wider range of soil test P concentrations to plot relationships similar to those reported in the literature. Soils at our site contained between 0.061 and 0.135 M3-PSR, which is generally less than the 0.131 P/Al ratio (determined by the Mehlich-3 P method) that was set as a critical environmental level in this province (Ministère de l'Environnement du Québec, 2002).

CONCLUSIONS

Agroecosystems with factorial combinations of tillage practices, cropping systems, and fertilizer sources were studied to determine how agricultural practices affected N and P leaching after crop harvest. We found that more NO_3–N and less dissolved reactive P was leached from soil cores receiving inorganic fertilizers than organic fertilizers. As much as 57% of the total N load was dissolved organic N, and as much as 50% of the total P load was dissolved organic P. These organic compounds could contribute to water pollution if they are transformed into NO_3–N and dissolved reactive P while transported through the soil profile or on reaching a water body such as a lake or ground water reservoir. The NO_3–N load in leachates was related to the soil NO_3–N concentration, while dissolved reactive P load in leachates was related to the soil Mehlich-3 P concentration and Mehlich-3 P saturation ratio. These soil tests may be used to predict the potential of dissolved N and dissolved P leaching from the topsoil to subsurface soils.

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