Effects of long-term tillage, terminating no-till and cropping system on organic C and N, and available nutrients in a Gleysolic soil in Québec, Canada

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Abstract

Some biological and chemical properties of a Gleysol were examined after 24 years of soil tillage (chisel plough – CP, mouldboard plough – MP, no-till – NT) and that of ploughing the 24-yr NT (P-NT) once, in two cropping systems (conventional – CONV, organic – ORG) applied over 4 years (2007–2010) of a long-term experiment (autumn 1987–autumn 2011) at La Pocatière, Québec, Canada. The 0–10, 10–20 and 20–30 cm soil depths were sampled in autumn 2011 after a maize trial. Tillage affected light fraction organic carbon (LFOC), light fraction organic nitrogen (LFON) and mineralizable N (N_{min}) in soil, with the lowest LFOC, LFON and N_{min} values in the MP treatment. No-till had lower soil pH than the other tillage systems in the 10–20 and 20–30 cm soil depths. Tillage affected the amounts of nitrate-N in 0–10 and 10–20 cm soil depths, with the lowest amounts for MP (4.3 kg nitrate-N/ha) compared with NT (7.2 or 8.5 kg nitrate-N/ha) or CP (7.7 kg nitrate-N/ha). The P-NT had no negative impact on organic C and N, or available nutrients in soil. Cropping system had no effect on soil organic C and N, available nutrients or pH. Findings suggest that long-term NT or CP may result in greater storage of organic C and N in soil and improve available nutrients compared with MP. Ploughing 25-year-old NT plots redistributed available nutrients in the profile but had no negative effect on soil organic C or N.

Introduction

Long-term performance and sustainability of crop production are linked to soil physical, chemical and biological properties, which in turn are influenced strongly by soil organic matter (SOM) (Weil and Magdoff, 2004). Soil organic matter improves soil properties and is a source of plant nutrients and energy for microorganisms. Quantity and quality of soil organic carbon (C) and nitrogen (N) are affected by soil and crop management practices (Liu *et al.*, 2006).

Tillage can affect the amounts of organic C stored in soil. For example, incorporation of crop residue under intensive tillage, especially mouldboard plough (MP), can cause substantial decrease in soil organic C and N by increasing decomposition rate (Douglas *et al.*, 1980; Collins *et al.*, 1992; Soon 1998; 2007). Leaving crop residue at the soil surface under no-tillage (NT) may restrict its decomposition, resulting in accumulation of SOM in the topsoil under NT (Liang *et al.*, 2004; Malhi and Lemke, 2007; Malhi *et al.*, 2011, 2012). Practicing MP tillage for 5–10 years may not cause any significant reduction in soil organic C and N compared with NT but may result in its redistribution in the soil profile (Angers *et al.*, 1997).

Long-term NT may cause stratification of P in the surface soil and reduce its availability to crops (Crozier *et al.*, 1999; Baan *et al.*, 2009). In areas where large amounts of crop residue or straw are produced, accumulated crop residue at the soil surface under NT may hinder seeding operations, resulting in poor/sporadic germination, especially when proper direct-seeding drills are not available to facilitate seeding. In addition, relatively cool and wet surface soil in spring under NT (Johnson and Lowery, 1985) may delay seeding and slow crop emergence and early growth and increase potential nutrient loss in surface water run-off (Ferguson *et al.*, 1996).

Current interest in low-input cropping systems often implies an increased use of tillage for weed control. Use of low-input or organic systems is also associated with a partial to total dependence on organic nutrient inputs. Application of organic manure can improve soil physical, chemical and biological properties, and the nutrient supplying power of the soil (Yanan *et al.*, 1997; Whalen *et al.*, 2001; Yang *et al.*, 2007; Heitkamp *et al.*, 2011). Organic cropping systems that include application of manure can increase organic C and N, and availability of nutrients in soil even after short-term (3 years) additions (Malhi, 2012).

At some point, producers could be interested in tilling long-term NT fields, partly because of the above-mentioned potential problems related to long-term use of NT, but also to make use of accumulated nutrients in surface soil under NT, particularly if transitioning to an organic cropping system. Effects of tillage applied to long-term NT on crop yield and nutrient uptake, available nutrients in soil, and persistence of organic C in soil that was gained/stored under NT have been investigated previously (Davidson and Ackerman, 1993; Campbell et al., 1998; VandenBygaart and Kay, 2004; Baan et al., 2009). However, effects of terminating NT with a ploughing operation on these variables in contrasted cropping systems (using conventional vs. organic inputs) have not been documented under the agro-environmental conditions of eastern Québec. The objective of the current study was to determine the effects of previous cropping system (conventional and organic), long term tillage (chisel plough (CP), MP, long-term NT and terminating NT (P-NT: NT ploughed once after 24 years) on soil organic C and N fractions (total organic C (TOC) and N (TON), light fraction organic carbon (LFOC) and nitrogen (LFON), and mineralizable N (N_{min})) and available nutrients in soil (ammonium-N, nitrate-N and extractable P) in the 0–10, 10–20 and 20–30 cm depths of a Gleysolic soil in Québec, Canada.

Materials and methods

The present study was initiated in autumn 1987 at the Centre de Développement Bioalimentaire du Québec, at La Pocatière, Québec, Canada (47°E 21′N, 70°E 02′W, 204 m a.s.l.), on a Kamouraska clay (Typic humic Gleysol, mineralogy dominated by illite and chlorite (400 g/kg), quartz and feldspars (300 g/kg) and smectites (170 g/kg) (De Kimpe et al., 1979); 100 g/kg sand, 300 g/kg silt, 600 g/kg clay (clay texture) in the surface horizon; pH = 5.9; organic matter = 45 g/kg; P-Mehlich 3 extractable = 94 kg/ha, K-Mehlich 3 extractable = 305 kg/ha). Tillage treatments included: MP (15–18 cm depth) in autumn, followed by spring secondary tillage; CP (12–15 cm depth) in autumn, followed by spring secondary tillage; and NT. Mouldboard plough and CP plots were ploughed every other year in the first phase of the study (1987–1995), and every year thereafter.

In 2007, the tillage plots were used to determine the feasibility of applying low-input cropping systems to mature conservation tillage plots (Légère et al., 2013). Two cropping systems were compared: (1) a system based on agronomic practices used in organic agriculture (ORG) (nutrients supplied as dry granular poultry manure and mechanical weed control), and a conventional cropping system (CONV) using synthetic nutrients and herbicide-based weed control. A 4-year crop rotation [barley (2007)/red clover (2008) (managed as a forage crop)/maize (2009)/soybean (2010)] was selected with the assumption that the initial barley/red clover years would provide good weed suppression as well as N input in support of the more demanding and less competitive maize crop.

Cropping system treatments were assigned randomly in strips perpendicular to the original tillage plots (plot size: 5 × 13 m^2) within each replicate, resulting in a strip plot design with four replicates. On 3 November 2010, each NT plot was further split in half lengthwise (2.5 × 13 m^2). One randomly selected half of NT was mouldboard ploughed (P-NT), whereas the other half remained in NT. This division created an additional treatment, i.e. terminated NT, to the existing tillage treatments (CP, MP and a non-terminated NT treatment) increasing the total number of tillage treatments in the experiment to four. On 10 June 2011, plots with MP, CP and P-NT were harrowed, and glyphosate-tolerant maize (Hybrid Fusion RR 2100-2400 CHU) was planted at 82 300 seeds/ha in 76 cm six rows. A reduced rate of fertilizer (220 kg/ha 27-18-0 N-phosphorus pentoxide (P_2O_5)–potassium oxide (K_2O)) was side-banded at planting to all plots to allow the expression of residual effects of previous cropping systems. Maize was harvested in autumn at maturity before frost kill. Details of the cropping system by tillage study are found in Légère et al. (2013). Treatments considered for the current soil study included MP, CP, NT and P-NT tillage in CONV and ORG cropping systems, for a total of eight treatments.

Soil sampling and sample preparation

On 27 October 2011, soil cores from five locations in the centre of plots were collected from the 0–10, 10–20 and 20–30 cm depths, using a 2.5 cm internal diameter corer. Bulk density of the soil was determined by the core method (Culley, 1993). Soil samples were air-dried at room temperature after removing any coarse roots and easily detectable crop residues, and ground to pass through a 2-mm sieve. Sub-samples were pulverized in a vibrating-ball mill (Retsch, Type MM2, Brinkman Instruments Co., Toronto, Ontario) for determination of organic C and N in various fractions.

Organic carbon and nitrogen analysis

For TON, soil samples were digested in concentrated sulphuric acid (H_2SO_4) plus one Keltab (containing 1.5 g potassium sulphate (K_2SO_4) and 0.15 g copper sulphate pentahydrate ($CuSO_4.5H_2O$)), and the ammonium in the digest was measured by using method of Technicon Industrial Systems (1977). Light fraction organic matter (LFOM) was separated using a sodium iodide (NaI) solution of 1.7 t/m^3 specific gravity, following the method described by Janzen et al. (1992) and modified by Izaurralde et al. (1998). The TOC, and C and N in LFOM (LFOC, LFON) were measured for the 0–10 and 10–20 cm depths by Dumas combustion using a Carlo Erba instrument (Model NA 1500, Carlo Erba Strumentazione, Italy). Soil samples of all depths for TOC and TON analyses were also tested to detect any inorganic C using dilute HCl (hydrochloric acid), but none was found.

Mineralizable N in soil for the 0–10, 10–20 and 20–30 cm depths was estimated from the quantities of ammonium-N and nitrate-N that were mineralized from an unfumigated sample during 10-day incubation at 25 °C and a soil water potential of −30 J/kg (Campbell et al., 1991). The concentrations of ammonium-N and nitrate-N were measured with a Technicon Analyzer II (Technicon Industrial Systems, 1973a, 1973b).

Chemical analysis

For chemical properties, prepared soil samples were analysed for pH, ammonium-N (NH_4-N), nitrate-N (NO_3-N) and extractable P (phosphate-P – PO_4-P). Soil pH was measured in dilute solution of calcium chloride ($CaCl_2$; 0.01 M) with a Fisher AR20 pH meter (San Diego, CA, USA). Nitrate-N and ammonium-N were extracted using 1:5 soil:2 M potassium chloride (KCl) solution and their concentrations in extracts determined with a Technicon Autoanalyzer II (Technicon Industrial Systems, 1973a, 1973b). Phosphorus was extracted using Kelowna soil extractant (Qian et al., 1994) and measured colorimetrically on a Technicon Autoanalyzer (Technicon Industrial Systems, 1977).

Statistical analysis

The data on TOC, TON, LFOC and LFON were calculated using the equivalent soil mass technique (Ellert and Bettany, 1995). Analysis of variance (ANOVA) was conducted separately for each depth using the GLIMMIX procedure of SAS (Littell *et al.*, 2006; SAS Institute, 2011). The analysis considered the effects of replicate, replicate by tillage and replicate by cropping system as random, the effects of cropping system and tillage were fixed, and used a Gaussian error distribution. The fixed effects were considered to be cross-classified factors for the analysis. Exploratory analysis indicated the possibility of heterogeneous variances among tillage systems for some of the tillage by depth combinations. The AICc (corrected Akaike's Information Criterion) was used to confirm the benefit of modelling variance heterogeneity (Littell *et al.*, 2006). Mean separation was performed using a protected least significant difference (LSD) test.

Results

The ANOVA table for the probabilities of significance for various parameters indicated that there was no significant tillage by cropping system interaction for all variables, except for pH in the 20–30 cm soil depth and LFON in the 0–10 cm soil depth (Table 1). Mean effect of tillage treatment was significant for LFOC and LFON in the 0–10 and 10–20 cm soil depths, pH in the 10–20 and 20–30 cm depths and N_{min} in all soil depths, and nitrate-N in the 0–10, 10–20 and 0–30 cm depths. Mean effect of cropping system treatments was significant only for TOC in the 0–10 cm soil depth (although the effect for TON was almost significant at $P = 0.057$). The results on various soil parameters are discussed in the following paragraphs.

The mass of TOC and TON varied with cropping system only in the 0–10 cm soil depth (Table 2). In the 0–10 cm soil depth, TOC in ORG (27.54 t C/ha) was 1.63 t C/ha greater ($P = 0.015$) than that in the CONV (25.91 t C/ha) cropping system. The effect of tillage on LFOC and LFON varied with soil depth (Table 2). In the 0–10 cm soil depth, TOC and TON values for MP tended to be lower (although not significantly) than for the other three tillage systems. In the 0–10 cm soil depth, LFOC and LFON in NT and CP were approximately twofold that in MP. In the P-NT treatment, mass of LFOC was similar to that of NT and CP, whereas mass of LFON was intermediate to that of MP *v.* CP and NT. In the 10–20 cm soil depth, mass of LFOC and LFON for MP and P-NT were nearly twofold that for NT and CP. Overall, LFOC and LFON were evenly distributed over the two soil layers in MP, predominant in the 0–10 cm depth for CP and NT, with intermediate values for P-NT which were 1.5 times greater in the 0–10 cm depth than that of 10–20 cm depth.

Tillage affected soil pH in the 10–20 and 20–30 cm soil depths, whereas cropping system had only a small effect on soil pH (Table 3). In the 10–20 and 20–30 cm soil depths, soil pH was lower in NT and P-NT than in MP and CP treatments. Also, in the 0–10 cm depth, soil pH tended to be lower in the P-NT and NT treatments, especially compared with the CP treatment.

The N_{min} value for MP was lower than for the other three tillage treatments in the 0–10 cm soil depth, lower for MP than for CP and P-NT in the 10–20 cm depth, and lower for MP than for NT and P-NT in the 20–30 cm depth (Table 3). No significant differences in N_{min} were observed among the other three tillage systems in all soil depths. Tillage affected nitrate-N only in the 0–10 and 10–20 cm soil depths, but again this effect varied with

soil depth (Table 3). In the 0–10 cm depth, nitrate-N for MP was lower than that for other tillage treatments whereas in the 10–20 cm depth, nitrate-N was lower for MP and NT than for P-NT, and not different from CP. Tillage and cropping system had no effect on ammonium-N (Table 3) or extractable P, although MP and P-NT tended to have lower extractable P in the 0–10 cm soil depth than NT and CP treatments (Table 4).

Discussion

Soil organic carbon and nitrogen

Both quantity and/or quality of organic matter in soil can be altered by tillage (Havlin *et al.*, 1990; Malhi and Lemke, 2007), crop rotation or cropping systems (Campbell *et al.*, 2001; Liang *et al.*, 2003; Malhi *et al.*, 2009). Tillage, especially MP, increases oxidation of SOM (Doran and Scott-Smith, 1987), while NT reduces its oxidation because of less mixing with the soil (Doran, 1980). Therefore, one would expect a decrease of organic C and/or N in soil under MP or CP compared with NT (Douglas *et al.*, 1980; Soon 1998, 2007). Similarly, in the present study after 25 years, the amounts of LFOC and LFON in soil, particularly in the 0–10 cm soil layer, were lower under MP than NT. But there were generally no significant differences in the amounts of TOC, TON, LFOC and LFON in soil between CP and NT systems. This could be due to the absence of inversion in CP, and to the depth of tillage/plough, which was shallower with CP (about 15 cm deep) than MP (about 20 cm deep).

In a review paper, Davidson and Ackerman (1993) summarized results from a number of studies varying in duration of tillage/cultivation of NT soils ranging from 3 to 100+ years, and in soil texture ranging from sandy loam to clay. It would appear that long-term untilled soils could lose 20–40% of their original organic C following tillage/cultivation (Davidson and Ackerman, 1993). However, in the present study, there was no significant negative effect of one-time ploughing on TOC, TON, LFOC and LFON in soil compared with the long-term NT treatment. Actually, one-time ploughing of NT resulted in increased productivity, as maize yield in 2011 was greater in P-NT than NT (Légère *et al.*, 2013). The absence of one-time ploughing effect on TOC, TON, LFOC and LFON in soil was also suggested by Baan *et al.* (2009) in their study in Saskatchewan, Canada. The soil in the present study was Humic Gleysol with a clay texture, whereas the soils in the Baan *et al.* (2009) study belonged to the Brown Chernozem, Black Chernozem and Gray Luvisol Great Groups, with loam, fine loam and silty clay loam/clay loam texture, respectively. In the Baan *et al.* (2009) studies, long-term NT soils were tilled/ploughed only once. It is anticipated that one-time ploughing of NT may increase both TOC and LFOC in soil in the future, because of its immediate beneficial effects on crop productivity (i.e., returning more crop residue to soil), due to the release/mineralization of nutrients tied in the LF organic matter.

Among the other dynamic fractions examined in the current study, N_{min} was also lower under MP than NT at 0–10 and 20–30 cm soil depths. This suggests that the soil N-reserve would improve with NT but diminish with MP. Soil N availability is usually the most limiting factor for crop production (Pastor *et al.*, 1984). Because the majority of available N used for synthesis of plant biomass is produced by mineralization from native soil organic N, this source of N should be considered when determining nutrient requirements of crops (Uri *et al.*, 2003). In the present study, greater soil N_{min} in NT than in MP suggests that

Table 1. Probability of significance for tested treatment effects of tillage, cropping system and tillage × cropping system interaction on total organic C (TOC), total organic N (TON), light fraction organic C (LFOC), light fraction organic N (LFON), pH, mineralizable N (N_{min}), nitrate-N (NO_3-N), ammonium-N (NH_4-N) and extractable P in the 0–10, 10–20, 20–30, 0–20 and 0–30 cm soil depths in autumn 2010 (after 24 growing seasons) in a field experiment established in autumn 1987 at La Pocatière, Québec, Canada

Parameter (tillage/system)	Soil depths (cm)					
	0–10	10–20	0–20	0–10	10–20	0–20
	TOC mass (t C/ha)			TON (t N/ha)		
	Probability of significance					
Tillage	ns	ns	Ns	ns	ns	ns
Cropping system	*	ns	Ns	ns	ns	ns
Tillage × cropping system	ns	ns	Ns	ns	ns	ns

Parameter	Soil depth (cm)					
	0–10	10–20	0–20	0–10	10–20	0–20
	LFOC mass (kg C/ha)			LFON mass (kg N/ha)		
	Probability of significance					
Tillage	**	**	Ns	**	*	ns
Cropping system	ns	ns	Ns	ns	ns	ns
Tillage × cropping system	ns	ns	Ns	*	ns	ns

Parameter	Soil depth (cm)						
	0–10	10–20	20–30	0–10	10–20	20–30	0–30
	Soil pH			Mineralizable N (kg N/ha)			
	Probability of significance						
Tillage	ns	*	**	***	*	*	**
Cropping system	ns	ns	Ns	ns	ns	ns	ns
Tillage × cropping system	ns	ns	*	ns	ns	ns	ns

Parameter	Soil depth (cm)							
	0–10	10–20	20–30	0–30	0–10	10–20	20–30	0–30
	NO_3-N (kg N/ha)				NH_4-N (kg N/ha)			
	Probability of significance							
Tillage	***	*	ns	*	ns	ns	ns	ns
Cropping system	ns	ns	ns	ns	ns	ns	ns	ns
Tillage × cropping system	ns	ns	ns	ns	ns	ns	ns	ns

Parameter	Soil depth (cm)			
	0–10	10–20	20–30	0–30
	Extractable P (kg P/ha)			
	Probability of significance			
Tillage	ns	ns	ns	ns
Cropping system	ns	ns	ns	ns
Tillage × cropping system	ns	ns	ns	ns

*, **, *** and ns refer to significant treatment effects in ANOVA at $P \leqslant 0.05$, $P \leqslant 0.01$, $P \leqslant 0.001$ and not significant, respectively.

the N-reserve of soil can be improved by reducing or eliminating tillage. There was a weak and non-significant correlation coefficient between crop yield and N_{min} in the 0–30 cm soil depth. For the other soil properties, the correlation coefficient between

crop yield and soil properties was significant only for soil NO_3-N in the 0–30 cm depth.

In the present study, the amounts of soil TOC in the 0–10 cm depth were greater under the ORG than the CONV cropping

Table 2. Effect of tillage and cropping system on mass of total organic C (TOC), total organic N (TON), light fraction organic C (LFOC) and light fraction organic N (LFON) in the 0–10, 10–20 and 0–20 cm soil depths in autumn 2010 in a field experiment established in autumn 1987 at La Pocatière, Québec, Canada

Treatment (tillage/system)	Soil depth (cm)					
	0–10	10–20	0–20	0–10	10–20	0–20
	TOC (t C/ha)			TON (t N/ha)		
Tillage						
Chisel plough	28	27	55	2.3	2.1	4.3
Mouldboard plough	23	24	48	1.9	1.9	3.8
No-tillage	27	23	51	2.3	1.8	4.1
One-time plough of no-tillage	28	27	55	2.3	2.2	4.4
LSD$_{0.05}$	4.7	5.3	9.8	0.39	0.38	0.75
	ns	ns	ns	ns	ns	ns
Cropping system						
Conventional	26	24	50	2.11	1.9	4.0
Organic	28	27	54	2.21	2.1	4.3
LSD$_{0.05}$	1.3	6.7	7.4	0.11	0.48	0.48
	ns	ns	ns	ns	ns	ns
	LFOC (kg C/ha)			LFON (kg N/ha)		
Tillage						
Chisel plough	663	230	893	256	8	32
Mouldboard plough	349	425	774	126	13	24
No-tillage	732	182	914	28	5	33
One-time plough of no-tillage	630	384	1014	19	14	33
LSD$_{0.05}$	173.0	139.8	230.4	10.1	8.1	12.9
	**	**	ns	**	*	ns
Cropping system						
Conventional	633	290	923	20	8	28
Organic	554	321	875	21	12	33
LSD$_{0.05}$	157.2	127.0	345.1	5.7	5.4	7.5
	ns	ns	ns	ns	ns	ns

*, ** and ns refer to significant treatment effects in ANOVA at $P \leqslant 0.05$, $P \leqslant 0.01$ and not significant, respectively.

system. This was probably due to the application of manure in the organic cropping system (Campbell *et al.*, 1986; McGill *et al.*, 1986; Yanan *et al.*, 1997; Whalen *et al.*, 2001; Assefa *et al.*, 2004; Heitkamp *et al.*, 2011; King *et al.*, 2015). Similarly, research in Saskatchewan, Canada, has also shown that ORG cropping systems, which include application of manure, can increase organic C and N, and availability of nutrients in soil even after short-term (3 years) additions (Malhi, 2012). However, in another 12-year long-term field research experiment in Saskatchewan where manure was applied occasionally, cropping system had no effect on TOC and TON in soil, although soil LFOC and LFON tended to be slightly greater under ORG than CONV cropping system (Malhi *et al.*, 2009), which is consistent with results of the present study. Manure has both direct and indirect input of C to soil, in some cases because of increased crop yields (Watson *et al.*, 2002). This was not the case in the present study since previous silage maize (2009) and soybean (2010) yield in ORG was reduced when compared with the CONV cropping system (Légère *et al.*,

2013). However, silage maize yield in 2011 (the present study) was similar across both cropping systems (Légère *et al.*, 2013).

Light fraction organic matter in soil reflects a balance between crop residue input, and their decomposition and persistence, depending on the soil-climatic conditions (Gulde *et al.*, 2008). The decomposition of LFOM is relatively faster than total organic matter in soil (Sollins *et al.*, 1984), and this could provide an increased supply of plant-available N and other nutrients to plants, maintain high microbial populations, enzyme activity and soil respiration rate, and improve soil physical properties (Gregorich *et al.*, 1997; Angers *et al.*, 1999; Lynch *et al.*, 2005*a*, 2005*b*; Marriott and Wander, 2006). Management practices can have a greater effect on LFOC and LFON than on TOC and TON (Malhi *et al.*, 2003*a*, 2003*b*, 2003*c*). Similarly, in the present study, the decreases in organic C and N for MP compared with NT were relatively more pronounced for LFOC and LFON than TOC, in spite of maize silage yield being similar across both tillage treatments (Légère *et al.*, 2013). Also, yield of previous soybean

Table 3. Effect of tillage and cropping system on pH, mineralizable N (N_{min}), nitrate-N (NO_3-N) and ammonium-N (NH_4-N) in the 0–10, 10–20, 20–30 and 0–30 cm soil depths in autumn 2010 (after 24 growing seasons) in a field experiment established in autumn 1987 at La Pocatière, Québec, Canada

Treatment (tillage/system)	Soil depth (cm)							
	0–10	10–20	20–30	0–30	0–10	10–20	20–30	0–30
	Soil pH				Mineralizable N (kg N/ha)			
Tillage								
Chisel plough	5.9	5.8	6.0		43	44	20	107
Mouldboard plough	5.8	5.8	6.1		25	30	16	70
No-tillage	5.7	5.5	5.6		56	33	25	114
One-time plough of No-tillage	5.7	5.6	5.6		46	43	28	117
$LSD_{0.05}$	0.24	0.23	0.23		13.2	11.2	9.2	24.5
	ns	*	**		***	*	**	**
Cropping system								
Conventional	5.8	5.7	5.9		41	36	21	98
Organic	5.7	5.7	5.8		44	39	24	106
$LSD_{0.05}$	0.35	0.15	0.17		9.3	15.0	10.3	32.2
	ns	ns	ns		ns	ns	ns	ns
	NO_3-N (kg N/ha)				NH_4-N (kg N/ha)			
Tillage								
Chisel plough	3	3	1.8	8	5	6	6	17
Mouldboard plough	2	2	1.1	4	5	5	4	14
No-tillage	3	2	1.9	7	5	6	5	15
One-time plough of No-tillage	4	3	1.7	9	5	6	5	15
$LSD_{0.05}$	1.3	1.2	0.7	2.8	1.0	1.1	1.8	3.5
	***	*	ns	**	ns	ns	ns	ns
Cropping system								
Conventional	3	2	1	6	5	6	5	15
Organic	3	3	2	8	5	6	5	16
$LSD_{0.05}$	0.8	0.8	0.4	1.7	0.7	0.8	1.5	2.5
	ns	ns	ns	ns	ns	ns	ns	ns

*, **, *** and ns refer to significant treatment effects in ANOVA at $P \leqslant 0.05$, $P \leqslant 0.01$, $P \leqslant 0.001$ and not significant, respectively.

(2010) and silage maize (2009) for NT was similar to MP yield for CONV cropping systems (Légère *et al*., 2013). The changes in LFOC and LFON can be considered good indicators of positive changes/build-up of organic C and N as a result of NT compared with MP (Hassink, 1994; Gagnon *et al*., 2001; Willson *et al*., 2001; Griffin and Porter, 2004). Monitoring the changes in LFOC and LFON in the surface soil would appear to be a good strategy to determine the potential for N supplying power, and improvement in soil quality/health. The higher organic C and N in light organic fractions than their total organic fractions under NT was most likely due to much slower decomposition of crop residue (straw, chaff, roots) under NT compared with MP treatment (Doran, 1980; Doran and Scott-Smith, 1987).

Overall, the findings of the present study suggest some potential of NT or CP in building-up of organic C and N in soil. This was associated with the improvement in some soil properties, such as nutrient supplying power (N_{min}). The increase in organic C and N in soil may also have some additional potential benefits, such

as improvement in soil biodiversity in NT as evidenced by earthworm communities (Eriksen-Hamel *et al*., 2009), and soil aggregation and water infiltration as well as decrease in water runoff and soil erosion, thereby increasing the sustainability of crop production (Malhi *et al*., 2006; Singh and Malhi, 2006; Malhi and Lemke, 2007).

Soil chemical properties

A trend of slow acidification (not significant) of surface soil under NT was observed after 12 annual applications of moderate rates of N fertilizer to annual crops in the Canadian prairies (Malhi *et al*., 2009). Similarly, in the present study, there was a slight decrease in soil pH to a depth of 30 cm under NT compared with CP or MP, most likely due to minimum disturbance and/or absence of mixing of surface/subsurface soil under NT compared with MP or CP for 24 years. Acidification of the surface soil from N fertilizer application does not appear to be a serious problem for cereal and oilseed crops at this site but may be an issue in the long run

Table 4. Effect of tillage and cropping system on extractable P in the 0–10, 10–20, 20–30 and 0–30 cm soil depths in autumn 2010 (after 24 growing seasons) in a field experiment established in autumn 1987 at La Pocatière, Québec, Canada

Treatment (tillage/system)	Extractable P (kg P/ha) in soil depths (cm)			
	0–10	10–20	20–30	0–30
Tillage				
Chisel plough	36	22	13	71
Mouldboard plough	18	19	10	47
No-tillage	30	17	12	59
One-time plough of no-tillage	21	20	12	53
LSD$_{0.05}$	17.7	13.9	11.4	40.0
	ns	ns	ns	ns
Cropping system				
Conventional	27	18	11	56
Organic	25	21	13	58
LSD$_{0.05}$	12.2	8.0	7.4	27.8
	ns	ns	ns	ns

ns refer to not significant treatment effects in ANOVA.

for optimum production of acid-sensitive crops. There was essentially no effect of cropping system on soil pH in the present study, as also suggested in a previous study where there was no consistent effect of crop diversity on soil pH decrease (Malhi *et al.*, 2009).

Treatments under long-term NT management have shown greater amounts of available P in the surface thin soil layer (0–5 cm or less) than mouldboard ploughing (Eckert, 1985; Weil *et al.*, 1988). Indeed, there was a trend for lower extractable P with MP compared with CP or NT in the present study. Maintaining higher concentration of readily plant-available P in soil near the surface should thus be facilitated where tillage is eliminated. This also suggests the need for additional application of P fertilizer under NT particularly in early years, because inorganic P at the soil surface under NT may not become fully available to the crop due to its relatively high immobility in the soil profile.

In the present study, the lower amounts of nitrate-N under MP compared with other tillage treatments could be due to a dilution effect of mixing soil to deeper depth, in addition to a greater potential of immobilization of N by straw (Malhi *et al.*, 1996), nitrate leaching to a deeper depth below 30 cm and gaseous N losses (Heaney *et al.*, 1992) under MP compared with CP or NT. Amounts of nitrate-N were relatively small even after 25 annual applications of N fertilizer. This could be due to moderate rate of N fertilizer in the present study, immobilization of applied N into the soil organic N pool, release of gaseous N over the winter and especially in early spring after snow melt and/or after occasional heavy rains in the growing season, and to nitrate-N leaching below the 30 cm depth. Downward movement of nitrate-N in the soil profile was not documented, because soil samples were taken only to 30 cm depth.

Conclusions

Long-term NT or CP would result in greater storage of organic C or N in soil and improve available nutrients in soil compared with MP. The one-time ploughing of long-term NT had no negative impact on organic C or N and available nutrients in soil. Elimination of tillage tended to cause some reduction in soil pH, especially in the 10–20 and 20–30 cm depths which may interfere with growth of acid-sensitive crops. Cropping system had little or no effect on soil organic C and N, available nutrients and pH.

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