The Journal of Agricultural Science

cambridge.org/ags

Crops and Soils Research Paper

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

S. S. Malhi[1,*], A. Légère[2], A. Vanasse[3] and G. Parent[4]

[1]Agriculture and Agri-Food Canada (AAFC), P.O. Box 1240, Highway 6 South Melfort, Saskatchewan S0E 1A0, Canada; [2]AAFC, Saskatoon Research Centre, 107 Science Drive, Saskatoon, Saskatchewan S7N 0X2, Canada; [3]Département de phytologie, Université Laval, Faculté des sciences de l'agriculture et de l'alimentation, 2425 rue de l'Agriculture, Québec, QC G1 V 0A6, Canada and [4]AAFC, 2560, boul. Hochelaga, Québec, QC G1 V 2J3, Canada

*Present address: Department of Renewable Resources, University of Alberta, Edmonton, Alberta T6G 2H1, Canada.

Cite this article: Malhi SS, Légère A, Vanasse A, Parent G (2018). 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. *The Journal of Agricultural Science* **156**, 472–480. https://doi.org/10.1017/S0021859618000448

Received: 25 November 2017
Revised: 9 March 2018
Accepted: 29 May 2018
First published online: 24 July 2018

Key words:
Available nutrients; chisel plough; cropping system; light fraction organic C and N; mouldboard plough; N fertilizer; no-till; organic crop production; total organic C and N

Author for correspondence:
G. Parent, E-mail: gaetan.parent@agr.gc.ca

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).

CAMBRIDGE
UNIVERSITY PRESS

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, 1973*a*, 1973*b*).

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, 1973*a*, 1973*b*). 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

	Soil depths (cm)					
Parameter (tillage/system)	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

	Soil depth (cm)					
Parameter	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

	Soil depth (cm)						
Parameter	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

	Soil depth (cm)							
Parameter	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

	Soil depth (cm)			
Parameter	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

	Soil depth (cm)					
Treatment (tillage/system)	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

	Soil depth (cm)							
Treatment (tillage/system)	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.

Acknowledgements. The authors thank Valérie Bélanger, Christine Juge and Maxime Boucher for field sampling, K. Strukoff for technical help, D. Leach and Dr F. C. Stevenson for statistical analyses and the field crew of the Centre de Développement Bioalimentaire du Québec in La Pocatière for their technical and field assistance.

Financial support. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Conflicts of interest. None.

Ethical standards. Not applicable.

References

Angers DA, Bolinder MA, Carter MR, Gregorich EG, Drury CF, Liang BC, Voroney RP, Simard RR, Donald RG, Beyaert RP and Martel J (1997) Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. *Soil & Tillage Research* **41**, 191–201.

Angers DA, Edwards LM, Sanderson JB and Bissonnette N (1999) Soil organic matter quality and aggregate stability under eight potato cropping sequences in a fine sandy loam of Prince Edward Island. *Canadian Journal of Soil Science* **79**, 411–417.

Assefa BA, Schoenau JJ and Grevers MCJ (2004) Effects of four annual applications of manure on Black Chernozemic soils. *Canadian Biosystems Engineering* **46**, 6.39–6.46. Identifier: c0403.

Baan CD, Grevers MCJ and Schoenau JJ (2009) Effects of a single cycle of tillage on long-term no-till prairie soils. *Canadian Journal of Soil Science* **89**, 521–530.

Campbell CA, Lafond GP, Zentner RP and Biederbeck VO (1991) Influence of fertilizer and straw baling on soil organic matter in a thin Black Chernozem in western Canada. *Soil Biology and Biochemistry* **23**, 443–446.

Campbell CA, Schnitzer M, Stewart JWB, Biederbeck VO and Selles F (1986) Effects of manure and P fertilizer on properties of Black Chernozem in southern Saskatchewan. *Canadian Journal of Soil Science* **66**, 601–613.

Campbell CA, Selles F, Lafond GP, Biederbeck VO and Zentner RP (2001) Tillage-fertilizer changes: effect on some soil quality attributes under long-term crop rotations in a thin Black Chernozem. *Canadian Journal of Soil Science* **81**, 157–165.

Campbell CA, Thomas AG, Biederbeck VO, McConkey BG, Selles F, Spurr D and Zentner RP (1998) Converting from no-tillage to pre-seeding tillage: influence on weeds, spring wheat grain yields and N, and soil quality. *Soil & Tillage Research* **46**, 175–185.

Collins HP, Rasmussen PE and Douglas Jr CL (1992) Crop rotation and residue management effects on soil carbon and microbial dynamics. *Soil Science Society of America Journal* **56**, 783–788.

Crozier CR, Naderman GC, Tucker MR and Sugg RE (1999) Nutrient and pH stratification with conventional and no-till management. *Communications in Soil Science and Plant Analysis* **30**, 65–74.

Culley JLB (1993) Density and compressibility. In Carter MR (ed.), *Soil Sampling and Methods of Analysis*. Boca Raton, FL: Lewis Publishers, pp. 529–549.

Davidson EA and Ackerman IL (1993) Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry* **20**, 161–193.

De Kimpe CR, Laverdière MR and Martel YA (1979) Surface area and exchange capacity of clay in relation to the mineralogical composition of Gleysolic soils. *Canadian Journal of Soil Science* **59**, 341–347.

Doran JW (1980) Soil microbial and biochemical changes associated with reduced tillage. *Soil Science Society of America Journal* **44**, 765–771.

Doran JW and Scott-Smith MS (1987) Organic matter management and utilization of soil and fertilizer nutrients. In Follett RF, Stewart JWB and Cole CV (eds), *Soil Fertility and Organic Matter as Critical Components* *of Production Systems*. SSSA Special Publication no. 19. Madison, WI: American Society of Agronomy, pp. 53–72.

Douglas Jr CL, Allmaras RR, Rasmussen PE, Ramig RE and Roager Jr NC (1980) Wheat straw composition and placement effects on decomposition in dryland agriculture of the Pacific Northwest. *Soil Science Society of America Journal* **44**, 833–837.

Eckert DJ (1985) Effects of reduced tillage on the distribution of soil pH and nutrients in soil profiles. *Journal of Fertilizer Issues* **2**, 86–90.

Ellert BH and Bettany JR (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science* **75**, 529–538.

Eriksen-Hamel NS, Speratti AB, Whalen JK, Légère A and Madramootoo CA (2009) Earthworm populations and growth rates related to long-term crop residue and tillage management. *Soil & Tillage Research* **104**, 311–316.

Ferguson AJD, Pearson MJ and Reynolds CS (1996) Eutrophication of natural water and toxic algal blooms. *Issues of Environmental Science and Technology* **5**, 27–41.

Gagnon B, Lalande R and Fahmy SH (2001) Organic matter and aggregation in a degraded potato soil as affected by raw and composted pulp residue. *Biology and Fertility of Soils* **34**, 441–447.

Gregorich EG, Carter MR, Doran JW, Pankhurst CE and Dwyer LM (1997) Biological attributes of soil quality. *Developments in Soil Science* **25**, 81–113.

Griffin TS and Porter GA (2004) Altering soil carbon and nitrogen stocks in intensively tilled two-year rotations. *Biology and Fertility of Soils* **39**, 366–374.

Gulde S, Chung H, Amelung W, Chang C and Six J (2008) Soil carbon saturation controls labile and stable carbon pool dynamics. *Soil Science Society of America Journal* **72**, 605–612.

Hassink J (1994) Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. *Soil Biology and Biochemistry* **26**, 1221–1231.

Havlin JL, Kissel DE, Maddux LD, Claassen MM and Long JH (1990) Crop rotation and tillage effects on soil organic carbon and nitrogen. *Soil Science Society of America Journal* **54**, 448–452.

Heaney DJ, Nyborg M, Solberg ED, Malhi SS and Ashworth J (1992) Overwinter nitrate loss and denitrification potential of cultivated soils in Alberta. *Soil Biology and Biochemistry* **24**, 877–884.

Heitkamp F, Raupp J and Ludwig B (2011) Soil organic matter pools and crop yields as affected by rate of farm yard manure and use of biodynamic preparation in a sandy soil. *Organic Agriculture* **1**, 111–124.

Izaurralde RC, Nyborg M, Solberg ED, Janzen HH, Arshad MA, Malhi SS and Molina-Ayala M (1998) Carbon storage in eroded soils after five years of reclamation techniques. In Lal R, Kimble JM, Follett RF and Stewart BA (eds), *Soil Processes and the Carbon Cycle*. Boca Raton, FL: CRC Press, pp. 369–385.

Janzen HH, Campbell CA, Brandt SA, Lafond GP and Townley-Smith L (1992) Light-fraction organic matter in soils from long-term crop rotations. *Soil Science Society of America Journal* **56**, 1799–1806.

Johnson MD and Lowery B (1985) Effect of three conservation tillage practices on soil temperature and thermal properties. *Soil Science Society of America Journal* **49**, 1547–1552.

King T, Schoenau JJ and Malhi SS (2015) Effect of application of liquid swine manure on soil organic carbon and enzyme activities in two contrasting Saskatchewan soils. *Sustainable Agriculture Research* **4**, 1–13.

Légère A, Vanasse A and Stevenson FC (2013) Low-input management and mature conservation tillage: Agronomic potential in a cool, humid climate. *Agronomy Journal* **105**, 745–754.

Liang BC, McConkey BG, Campbell CA, Curtin D, Lafond GP, Brandt SA and Moulin AP (2004) Total and labile soil organic nitrogen as influenced by crop rotations and tillage in Canadian prairie soils. *Biology and Fertility of Soils* **39**, 249–257.

Liang BC, McConkey BG, Schoenau J, Curtin D, Campbell CA, Moulin A, Lafond GP, Brandt SA and Wang H (2003) Effect of tillage and crop rotations on the light fraction organic carbon and carbon mineralization in Chernozemic soils of Saskatchewan. *Canadian Journal of Soil Science* **83**, 65–72.

Littell RC, Milliken GA, Stroup WW and Wolfinger RD (2006) *SAS® System for Mixed Models*, 2nd Edn. Cary, NC: SAS Institute Inc.

Liu X, Hebert SJ, Hashemi AM, Zhang X and Ding G (2006) Effects of agricultural management on soil organic matter and carbon transformation – a review. *Plant, Soil and Environment* **52**, 531–543.

Lynch DH, Cohen RDH, Fredeen A, Patterson G and Martin RC (2005*a*) Management of Canadian prairie region grazed grasslands: soil C sequestration, livestock productivity and profitability. *Canadian Journal of Soil Science* **85**, 183–192.

Lynch DH, Voroney RP and Warman PR (2005*b*) Soil physical properties and organic matter fractions under forages receiving composts, manure or fertilizer. *Compost Science and Utilization* **13**, 252–261.

Malhi SS (2012) Short-term residual effects of various amendments on organic C and N, and available nutrients in soil under organic crop production. *Agricultural Sciences* **3**, 375–384.

Malhi SS and Lemke R (2007) Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-yr rotation cycle. *Soil & Tillage Research* **96**, 269–283.

Malhi SS, Brandt S and Gill KS (2003*a*) Cultivation and grassland type effects on light fraction and total organic C and N in a Dark Brown Chernozemic soil. *Canadian Journal of Soil Science* **83**, 145–153.

Malhi SS, Brandt SA, Lemke R, Moulin AP and Zentner RP (2009) Effects of input level and crop diversity on soil nitrate-N, extractable P, aggregation, organic C and N, and nutrient balance in the Canadian Prairie. *Nutrient Cycling in Agroecosystems* **84**, 1–22.

Malhi SS, Harapiak JT, Nyborg M, Gill KS, Monreal CM and Gregorich EG (2003*b*) Light fraction organic N, ammonium, nitrate and total N in a thin Black Chernozemic soil under bromegrass after 27 annual applications of different N rates. *Nutrient Cycling in Agroecosystems* **65**, 201–210.

Malhi SS, Harapiak JT, Nyborg M, Gill KS, Monreal CM and Gregorich EG (2003*c*) Total and light fraction organic C in a thin Black Chernozemic grassland soil as affected by 27 annual applications of six rates of fertilizer N. *Nutrient Cycling in Agroecosystems* **66**, 33–41.

Malhi SS, Lemke R, Wang ZH and Chhabra BS (2006) Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality, and greenhouse gas emissions. *Soil & Tillage Research* **90**, 171–183.

Malhi SS, Nyborg M, Goddard T and Puurveen D (2011) Long-term tillage, straw and N rate effects on quantity and quality of organic C and N in a Gray Luvisol soil. *Nutrient Cycling in Agroecosystems* **90**, 1–20.

Malhi SS, Nyborg M, Goddard T and Puurveen D (2012) Long-term tillage, straw management and N fertilization effects on macro organic matter and mineralizable C and N in a Black Chernozem soil. *Communications in Soil Science and Plant Analysis* **43**, 2679–2690.

Malhi SS, Nyborg M and Solberg ED (1996) Influence of source, method of placement and simulated rainfall on the recovery of ^{15}N-labelled fertilizers under zero tillage. *Canadian Journal of Soil Science* **76**, 93–100.

Marriott EE and Wander M (2006) Qualitative and quantitative differences in particulate organic matter fractions in organic and conventional farming systems. *Soil Biology and Biochemistry* **38**, 1527–1536.

McGill WB, Cannon KR, Robertson JA and Cook FD (1986) Dynamics of soil microbial biomass and water-soluble organic C in Breton L after 50 years of cropping to two rotations. *Canadian Journal of Soil Science* **66**, 1–19.

Pastor J, Aber JD, McClaugherty CA and Melillo JM (1984) Aboveground production and N and P cycling along a nitrogen mineralization gradient on Blackhawk Island, Wisconsin. *Ecology* **65**, 256–268.

Qian P, Schoenau JJ and Karamanos RE (1994) Simultaneous extraction of phosphorus and potassium with a new soil test: a modified Kelowna extraction. *Communications in Soil Science and Plant Analysis* **25**, 627–635.

SAS Institute (2011) *SAS/STAT® 9.3 User's Guide*. Cary, NC: SAS Institute Inc.

Singh B and Malhi SS (2006) Response of soil physical properties to tillage and residue management on two soils in a cool temperate environment. *Soil & Tillage Research* **85**, 143–153.

Sollins P, Spycher G and Glassman CA (1984) Net nitrogen mineralization from light- and heavy-fraction forest soil organic matter. *Soil Biology and Biochemistry* **16**, 31–37.

Soon YK (1998) Crop residue and fertilizer management effects on some biological and chemical properties of a Dark Grey Solod. *Canadian Journal of Soil Science* **78**, 707–713.

Soon YK (2007) Straw removal increases the light fraction and mineralizable C and N compared with moldboard ploughing. *Canadian Journal of Soil Science* **87**, 113–115.

Technicon Industrial Systems (1973*a*) *Ammonium in Water and Waste Water*. Industrial Method No. 90-70W-B. Revised January 1978. Tarrytown, NY: Technicon Industrial Systems.

Technicon Industrial Systems (1973*b*) *Nitrate in Water and Waste Water*. Industrial Method No. 100-70W-B. Revised January 1978. Tarrytown, NY: Technicon Industrial Systems.

Technicon Industrial Systems (1977) *Industrial/Simultaneous Determination of Nitrogen and/or Phosphorus in BD Acid Digests*. Industrial method no. 334-74W/Bt. Tarrytown, NY: Technicon Industrial Systems.

Uri V, Lõhmus K and Tullus H (2003) Annual net nitrogen mineralization in a grey alder (*Alnus incana* (L.) moench) plantation on abandoned agricultural land. *Forest Ecology and Management* **184**, 167–176.

VandenBygaart AJ and Kay BD (2004) Persistence of soil organic carbon after plowing a long-term no-till field in southern Ontario, Canada. *Soil Science Society of America Journal* **68**, 1394–1402.

Watson CA, Atkinson D, Gosling P, Jackson LR and Rayns FW (2002) Managing soil fertility in organic farming systems. *Soil Use and Management* **18**, 239–247.

Weil RR and Magdoff F (2004) Significance of soil organic matter to soil quality and health. In Magdoff F and Weil RR (eds), *Soil Organic Matter in Sustainable Agriculture*. Boca Raton, FL: CRC Press, pp. 1–43.

Weil RR, Benedetto PW, Sikora LJ and Bandel VA (1988) Influence of tillage practices on phosphorus distribution and forms in three Ultisols. *Agronomy Journal* **80**, 503–509.

Whalen JK, Chang C and Olson BM (2001) Nitrogen and phosphorus mineralization potentials of soils receiving repeated annual cattle manure applications. *Biology and Fertility of Soils* **34**, 334–341.

Willson TC, Paul EA and Harwood RR (2001) Biologically active soil organic matter fractions in sustainable cropping systems. *Applied Soil Ecology* **16**, 63–76.

Yanan T, Emteryd O, Dianqing L and Grip H (1997) Effect of organic manure and chemical fertilizer on nitrogen uptake and nitrate leaching in a Eum-orthic anthrosols profile. *Nutrient Cycling in Agroecosystems* **48**, 225–229.

Yang S-M, Malhi SS, Li F-M, Suo D-R, Xu M-G, Wang P, Xiao G-J, Jia Y, Guo T-W and Wang J-G (2007) Long-term effects of manure and fertilization on soil organic matter and quality parameters of a calcareous soil in NW China. *Journal of Plant Nutrition and Soil Science* **170**, 234–243.