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ORIGINAL ARTICLE

Long-term tillage, straw management and N fertilization effects on quantity and quality of organic C and N in a Black Chernozem soil

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Abstract Soil, crop and fertilizer management practices may affect the amount and quality of organic C and N in soil. A long-term field experiment (growing barley, wheat, or canola) was conducted on a Black Chernozem (Albic Argicryoll) loam at Ellerslie, Alberta, Canada, to determine the influence of 19 (1980 to 1998) or 27 years (1980 to 2006) of tillage (zero tillage [ZT] and conventional tillage [CT]), straw management (straw removed [S_{Rem}]and straw retained [S_{Ret}]) and N fertilizer rate (0, 50 and 100 kg N ha^{-1} in S_{Ret} and 0 kg N ha^{-1} in S_{Rem} plots) on total organic C (TOC) and N (TON), and light fraction organic C (LFOC) and N (LFON) in the 0–7.5 and 7.5–15 cm or 0–5, 5–10 and 10–15 cm soil layers. The mass of TOC and TON in soil was usually higher in S_{Ret} than in S_{Rem} treatment (by 3.44 Mg C ha^{-1} for TOC and 0.248 Mg N ha^{-1} for TON after 27 years), but there was little effect of tillage and N fertilization on these parameters. The mass of LFOC and LFON in soil tended to increase with S_{Ret} (by 285 kg C ha^{-1} for LFOC and 12.6 kg N ha^{-1} for LFON with annual rate of 100 kg N ha^{-1} for 27 years), increased with N fertilizer application (by 517 kg C ha^{-1} for LFOC and 36.0 kg N ha^{-1} for LFON after 27 years), but was usually higher under CT than ZT (by 451 kg C ha^{-1} for LFOC and 25.3 kg N ha^{-1} for LFON after 27 years). Correlations between soil organic C or N fractions were highly significant in most cases. Linear regressions between crop residue C input and soil organic C or N were significant in most cases. The effects of tillage, straw management and N fertilizer on soil were more pronounced for LFOC and LFON than TOC and TON, and also in the surface layers than in the deeper layers. Tillage and straw management had little or no effect on C:N ratios, but the C:N ratios in light organic fractions significantly decreased with increasing N rate (from 20.06 at zero-N to 18.91 at 100 kg N ha^{-1}). Compared to the 1979 results, in treatments that did not receive N fertilizer ($CTS_{Rem}0$, $CTS_{Ret}0$, $ZTS_{Rem}0$ and $ZTS_{Ret}0$), $CTS_{Rem}0$ resulted in a net decrease in TOC concentration (by 1.9 g C kg^{-1}) in the 0–15 cm soil layer in 2007 (after 27 years), with little or no change in the $CTS_{Ret}0$ and $ZTS_{Rem}0$ treatments, while there was a net increase in TOC concentration (by 1.2 g C kg^{-1}) in the $ZTS_{Ret}0$ treatment. Straw retention and N fertilizer application at 50 and 100 kg N ha^{-1} rates showed a net positive effect on TOC concentration under both ZT ($ZTS_{Ret}50$ by 2.3 g C kg^{-1} and $ZTS_{Ret}100$ by 3.1 g C kg^{-1}) and CT ($CTS_{Ret}50$ by 3.5 g C kg^{-1} and $CTS_{Ret}100$ by 1.6 g C kg^{-1}) treatments in 2007 compared to 1979

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data. In conclusion, the findings suggest that retention of straw, application of N fertilizer and elimination of tillage would improve soil quality, and this might increase the potential for N supplying power of the soil and sustainability of crop productivity.

Keywords Crop residue · Dynamic organic fractions · Light fraction organic matter · No-tillage · Soil quality · Total organic matter · Zero-tillage

Introduction

In western Canada, cultivation of native prairie grasslands over more than 100 years has resulted in a considerable loss of organic C in soil (McGill et al. 1981, 1988). This rapid decline of soil organic C (SOC) was attributed to a cultivated annual cropping system, using tillage and summer fallow. Adoption of management practices, such as continuous cropping, reduced tillage, increased fertilization, application of organic amendments and increased perennial forage production can increase the amount of C stored in the soil (Soon and Arshad 1996; Izaurralde et al. 1997; Janzen et al. 1998; Campbell et al. 2001; Liang et al. 2002, 2003, 2004; Malhi et al. 2008, 2009). Subsequently, soils can function as a sink for C and a nutrient reservoir for plants and microorganisms (Ndayegamiye et al. 1997; Sleutel et al. 2006) and improve soil fertility (Janzen 2006) and agricultural productivity (Robertson and Swinton 2005). However, changes in SOC are difficult to detect in the short term due to the slow build up of organic matter in soil. Research has shown that dynamic organic C fractions are useful to detect changes in SOC in the early years of a new management practice (Gregorich et al. 1994; Doran and Parkin 1994). So, measurement of the dynamic organic C and nitrogen (N) fractions (light fraction organic C [LFOC] and N [LFON]) in soils may allow researchers to quickly assess the changes in soil organic matter (SOM) in response to new management practices.

Light fraction organic matter (LFOM) in soil is considered to be in balance between crop residue input, and its decomposition (Gregorich and Janzen 1995). Because the decomposition of LFOM is relatively rapid compared with the SOM (Sollins et al. 1984; Bonde et al. 1992), it can act as a source of N and other nutrients for plants and microorganisms, maintain enzyme activity and respiration in soil, and improve soil properties (Kanazawa and Philip 1986; Janzen et al. 1992; Carter et al. 1994; Singh and Malhi 2006). Earlier research has shown that changes in the LFOC and LFON were more responsive to elimination of tillage, straw retention and N fertilization than TOC and TON (Bremer et al. 1995; Solberg et al. 1997; Malhi and Lemke 2007). Therefore, this also suggests that monitoring of the changes in LFOC and LFON in the surface soil appears to be a good strategy to determine the potential for N supplying power, and improvement in soil fertility and soil quality or health.

In western Canada, the use of zero-tillage (ZT, also called no-till or direct seeding) has increased substantially and is still increasing in part because it prevents soil erosion and reduces loss of C. There is limited information on the long-term effects of soil, crop and nutrient management practices on quantity and quality of soil organic matter. The objective of this study was to determine the long-term effects of tillage, straw management and N fertilization on total organic C (TOC) and N (TON), and light fraction organic C (LFOC) and N (LFON) after 19 or 27 crop growing seasons in a Black Chernozem (Albic Argicryoll) soil at Ellerslie, Alberta, Canada.

Materials and methods

Location and experimentation

The field experiment was located near Ellerslie (53°25′N, 113°33′W; elevation 692 m), Alberta. This area belongs to the Aspen Parkland ecological region, which is characterized by a flat glacio-lacustrine landscape. The soil is a Black Chernozem (Albic Argicryoll), with loam texture, pH 6.0 and initial total organic C concentration of 56.45 g C kg^{-1}. The mean annual precipitation of the area is about 450 mm and the growing season is from May to August. Approximately 60% of the total precipitation occurs in the growing season (335 mm with a range of 190 to 440 mm). This area has growing degree days (GDD) of 2,419 at >0°C and GDD of 1,402 at >5°C, a 120 day frost free period, and a mean daily temperature of 14°C (8 to 21°C) in the growing season.

The experiment was initiated in the autumn of 1979. The treatments were arranged in a randomized complete block design in four replications. Initially, the plots were under continuous barley (*Hordeum vulgare* L.) rotation with conventional tillage [CT] and zero tillage [ZT]) systems, straw removed [S_{Rem}] and straw retained [S_{Ret}] treatments, and 0 and 56 kg N ha^{-1} N treatments (Nyborg et al. 1995). In 1991, a 100 kg N ha^{-1} treatment was added and the 56 kg N ha^{-1} rate was reduced to 50 kg N ha^{-1}. From 1999 to 2006, the rotation was canola (*Brassica napus* L.)-triticale (*X Tricosecale*, Wittmack)-pea (*Pisum sativum* L.)-wheat (*Triticum aestivum* L.)/barley rotation. Barley was substituted for wheat when seeding dates were delayed. Individual plots were 2.8 × 6.9 m. Plots under CT were aggressively tilled once in the spring prior to seeding with a rotary tiller. The ZT plots did not undergo any disturbance, except by the seeding drill with low disturbance double disc openers. Crops were harvested from 1980 to 2006, for seed and straw yield. In autumn 1998 and spring 2007, soil samples were taken from selected treatments in the wheat phase (Table 1). The soil samples were analyzed for various organic C and N fractions and some chemical properties.

Soil sampling and laboratory analysis

Soil sampling and sample preparation

For autumn 1998 soil samples, a standardized sampling protocol for C assessment developed by Ellert and Janzen (1996) and modified for plot sampling. Three cores (9.5-cm diameter) per plot were bulked for the 0–7.5, 7.5–15, 15–30 and 30–40 cm soil layers. Soil samples were air dried for 2 weeks after removing coarse roots and easily detectable crop residues, weighed, and bulk densities calculated using soil weight and core volume (Culley 1993). Air-dried soil samples were ground to pass 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.

For spring 2007 sampling, soil samples at 8 locations in each plot were collected from the 0–5, 5–10, 10–15, and 15–20 cm layers using a 2.4 cm diameter coring tube. Bulk density, air drying, grinding and pulverization of soil samples for determination of organic C and N was done as described previously.

Organic C and N analysis

Representative soil sub-samples of all layers from both autumn 1998 and spring 2007 samplings were analyzed for total and light fraction organic C and N. The TON was measured with a Technicon Autoanalyzer (Technicon Industrial Systems 1977), and TOC was measured by Dumas combustion using a Carlo Erba instrument (Model NA 1500, Carlo Erba Strumentazione, Italy). Light fraction organic matter (LFOM) was separated using a NaI solution of 1.7 Mg m^{-3} specific gravity, following the method

Table 1 Description of treatments sampled in autumn 1998 and in spring 2007, and cumulative crop residue C input (Mg C ha-1) in 1980–1998 and 1980–2006 growing seasons at Ellerslie, Alberta, Canada (Black Chernozem soil, experiment established in autumn 1979)

Treatment	ID	Tillage system	Straw disposal	Rate of N (kg N ha^{-1})	Cumulative crop residue C input (Mg C ha-1) in growing seasons	
					1980–1998	1980–2006
1	$ZTS_{Rem}0$	Zero	Straw removed	0	6.463	9.351
4	$ZTS_{Ret}0$	Zero	Straw retained	0	21.091	32.265
3	$ZTS_{Ret}50$	Zero	Straw retained	50	37.054	51.502
6	$ZTS_{Ret}100$	Zero	Straw retained	100	38.848	57.212
2	$CTS_{Rem}0$	Conventional	Straw removed	0	7.951	10.961
5	$CTS_{Ret}0$	Conventional	Straw retained	0	25.060	36.104
8	$CTS_{Ret}50$	Conventional	Straw retained	50	43.758	60.932
7	$CTS_{Ret}100$	Conventional	Straw retained	100	42.414	60.872

described by Janzen et al. (1992) and modified by Izaurralde et al. (1997). The C and N in LFOM (LFOC and LFON) were measured by Dumas combustion using a Carlo Erba instrument (Model NA 1500, Carlo Erba Strumentazione, Italy). Soil samples from all layers for organic C analyses were tested for the presence of inorganic C (carbonates) using dilute HCl. Inorganic C was not detected in any soil sample, so the C in each soil fraction was considered to be of organic origin. The C content solublized during the fractionation procedure was not dosed and that losses for mass, C and N contents during fractionation procedure were not estimated.

Determination of cumulative crop residue or crop residue C input

The amount of cumulative crop residue (CR) returned to the soil from 1980 to 1998 or 2006 growing seasons was estimated as aboveground residue (AGR) plus belowground residue (BGR) returned to soil. The AGR was recorded from straw yield of each crop. The BGR was estimated from grain dry weight (GDW) and AGR, using formula: BGR = a (GDW + AGR). Based on regression models developed in Canada (IPCC 2006), the value of the constant 'a' was 0.22 for barley, 0.24 for wheat and 0.25 for canola. The amounts of crop residue C input were estimated by multiplying the concentration of C by the amount of crop residue. The estimated C concentration was 44% for barley residue (Nyborg et al. 1995), 45% for wheat and 42% for canola (Lupwayi et al. 2007). The cumulative amounts of CR-C (AGR-C + BGR-C) inputs in various treatments for the growing seasons from 1979 to 1998 (19 years) and from 1979 to 2006 (27 years) are presented in Table 1.

Historical comparisons of TOC concentration in soil

Because there was limited information from the samples in 1979 and 1990 (no bulk density), the mean bulk density for the 0–7.5 and 7.5–15 cm soil layers was then used to back calculate 1998 TOC mass values (Mg C ha^{-1}) into g C kg^{-1}. The lack of information from 1979 and 1990 also prevented comparison on an equivalent soil mass (ESM) basis. Therefore g C kg^{-1} in the 1998 samples was based on a fixed depth (0–15 cm). A similar procedure was used to calculate concentration of TOC (g C kg^{-1}) in 0–15 cm soil for spring 2007 samples.

Statistical analysis

The amounts of TOC, TON, LFOC and LFON were calculated using the ESM technique (Ellert and Bettany 1995). These data were subjected to analysis of variance (ANOVA) using procedures as outline in SAS (SAS Institute 2004). Significant ($P \leq 0.05$) differences between each treatment were determined using LSmeans (Proc GLM, SAS 6.1 for Windows). *F*-test values, *F*-test probabilities *P* and error mean squares (EMS) and least significant differences ($LSD_{0.05}$) of ANOVA for various parameters are presented in tables. Contrasts were also calculated for comparing tillage (ZT vs. CT), straw management (S_{Ret} vs. S_{Rem} for the zero-N treatment) and N rate (0 vs. 50 kg N ha^{-1}, 0 vs. 100 kg N ha^{-1}, and 50 vs. 100 kg N ha^{-1}) treatments. Correlations between treatment means of the TOC, TON, LFOC, LFON, and crop residue C were calculated by using the linear regression (REG) procedure.

Results

Total organic C and N

Autumn 1998 soil samples

There was no significant effect of tillage and N fertilizer application on the mass of TOC and TON in any soil layer, but TOC and TON were significantly higher in S_{Ret} than in S_{Rem} treatment in the 0–5 and 0–15 cm soil layers (Table 2). In the 0–15 cm soil layer, straw retention increased TOC by 3.78 Mg C ha^{-1} and TON by 0.285 Mg N ha^{-1} compared to straw removal over the 19 year period. There was no effect of any treatment on TOC and TON in the 15–30 and 30–40 cm soil layers (data not shown).

Spring 2007 soil samples

The mass of TOC was significantly affected only by straw management in the 0–5 and 0–15 cm soil layers (Table 3). Compared to S_{Rem} treatment, the S_{Ret} treatment resulted in an average increase of TOC

Table 2 Effect of long-term tillage, straw and N rate on mass of soil total organic C (TOC) and total organic N (TON) in soil in autumn 1998 at Ellerslie, Alberta, Canada (Black Chernozem soil, experiment established in autumn 1979)

Treatment[a] (tillage/straw/kg N ha^{-1})	TOC mass (Mg C ha^{-1}) in soil layers (cm)			TON mass (Mg N ha^{-1}) in soil layers (cm)		
	0–7.5	7.5–15	0–15	0–7.5	7.5–15	0–15
Treatment effect						
$ZTS_{Rem}0$	48.62	44.74	93.35	4.273	3.943	8.215
$ZTS_{Ret}0$	50.39	45.73	96.11	4.405	3.998	8.403
$ZTS_{Ret}50$	49.40	46.01	96.01	4.330	4.105	8.435
$ZTS_{Ret}100$	51.35	46.18	97.53	4.500	4.095	8.595
$CTS_{Rem}0$	46.38	42.57	88.95	4.080	3.815	7.895
$CTS_{Ret}0$	48.83	44.91	93.74	2.290	3.988	8.278
$CTS_{Ret}50$	51.30	46.15	97.45	4.508	4.118	8.625
$CTS_{Ret}100$	49.56	45.53	95.08	4.383	4.093	8.475
ANOVA						
F-test value	1.36	0.58	1.24	1.56	0.69	1.59
F-test probability *P*	0.2744	0.7660	0.3272	0.2027	0.6793	0.1926
Error mean squares (EMS)[b]	7.75102	11.2621	25.4979	0.049214	0.063907	0.140031
Tillage effect						
ZT mean[c]	49.94a	45.81a	95.75a	4.377a	4.035a	8.412a
CT mean	49.02a	44.79a	93.80a	4.315a	4.003a	8.318a
$LSD_{0.05}$	2.12^{ns}	2.31^{ns}	3.76^{ns}	0.173^{ns}	0.179^{ns}	0.294^{ns}
Straw effect at 0 N						
S_{Rem}mean	47.50a	43.65a	91.15a	4.176a	3.879a	8.055a
S_{Ret} mean	49.61b	45.32a	94.93b	4.348b	3.993a	8.340b
$LSD_{0.05}$	2.11*	2.22^{ns}	3.66*	0.170*	0.169^{ns}	0.265*
N rate effect for S_{Ret}						
0 mean	49.61a	45.32a	94.93a	4.348a	3.993a	8.340a
50 mean	50.35a	46.38a	96.73a	4.419a	4.111a	8.530a
100 mean	50.45a	45.85a	96.31a	4.441a	4.094a	8.535a
$LSD_{0.05}$	3.21^{ns}	3.08^{ns}	3.12^{ns}	0.253^{ns}	0.224^{ns}	0.367^{ns}

Asterisk and ns refer to significant treatment effects in ANOVA at $P \leq 0.05$ and not significant, respectively

[a] *ZT* zero tillage, *CT* conventional tillage, S_{Rem} straw removed, S_{Ret} straw retained, 0, 50 and 100 kg N ha^{-1}

[b] Also named Residual Mean Square (RMS). All ANOVA values from the ANOVA table, not presented

[c] The difference between two means followed by the same letter is not statistically significant at $P \leq 0.05$

mass by 3.44 Mg C ha^{-1} in the 0–15 cm soil layer. The mass of TOC in the 0–5 cm soil layer tended to be higher (by 1.18 Mg C ha^{-1}, but not significant) under ZT than CT. A fertilizer rate of 50 kg N ha^{-1} tended to increase (but not significant) TOC by 1.25 Mg C ha^{-1} in the 0–5 cm soil layer, but there were no differences between the 50 and 100 kg N ha^{-1} rates. The response trends of TON in different soil layers to tillage, straw management and N fertilization were usually similar to TOC (Table 3).

Light fraction organic C and N

Autumn 1998 soil samples

The mass of LFOC in soil increased significantly with N fertilization in the 0–7.5 and 0–15 cm soil layers (Table 4). In the 0–15 cm soil layer, the mass of TOC increased by 473 kg C ha^{-1} as the N rate increased from 0 to 100 kg N ha^{-1} and tended to be higher (by 265 kg C ha^{-1}) in S_{Ret} than in S_{Rem} treatment, but lower under ZT compared to CT. Soil LFON mass

Table 3 Effect of long-term tillage, straw and N rate on mass of soil total organic C (TOC) and total organic N (TON) in soil in spring 2007 at Ellerslie, Alberta, Canada (Black Chernozem soil, experiment established in autumn 1979)

Treatment[a] (tillage/straw/kg N ha^{-1})	TOC (Mg C ha^{-1}) at soil depths (cm)				TON (Mg N ha^{-1}) at soil depths (cm)			
	0–5	5–10	10–15	0–15	0–5	5–10	10–15	0–15
Treatment effect								
$ZTS_{Rem}0$	26.95	31.16	28.64	86.74	2.307	2.691	2.470	7.469
$ZTS_{Ret}0$	29.03	31.00	29.86	89.88	2.462	2.662	2.595	7.720
$ZTS_{Ret}50$	29.83	32.04	29.33	91.20	2.513	2.738	2.513	7.763
$ZTS_{Ret}100$	30.47	31.92	29.79	92.17	2.574	2.741	2.519	7.833
$CTS_{Rem}0$	26.14	30.24	28.25	84.63	2.224	2.601	2.443	7.269
$CTS_{Ret}0$	27.64	31.94	28.79	88.37	2.301	2.736	2.476	7.514
$CTS_{Ret}50$	29.34	33.20	30.65	93.19	2.471	2.819	2.619	7.909
$CTS_{Ret}100$	28.46	32.60	28.83	89.89	2.396	2.791	2.471	7.657
ANOVA								
F-test value	4.78	1.63	0.86	1.97	4.57	1.67	0.95	1.92
F-test probability *P*	0.0024	0.1817	0.5508	0.1088	0.0031	0.1718	0.4921	0.1168
Error mean squares (EMS)[b]	1.83516	2.16811	2.89997	16.4135	0.01260	0.01179	0.01676	0.09351
Tillage effect								
ZT mean[c]	29.07a	31.53a	29.40a	90.00a	2.464a	2.708a	2.542a	7.696a
CT mean	27.89a	32.00a	29.13a	89.02a	2.348b	2.737a	2.502a	7.587a
$LSD_{0.05}$	1.32^{ns}	1.16^{ns}	1.23^{ns}	3.31^{ns}	0.105*	0.086^{ns}	0.095^{ns}	0.247^{ns}
Straw effect at 0 N								
S_{Rem} mean	26.54a	30.70a	28.44a	85.69a	2.566a	2.646a	2.457a	7.369a
S_{Ret} mean	28.33b	31.47a	29.33a	89.13b	2.382b	2.699a	2.536a	7.617a
$LSD_{0.05}$	1.65*	1.18^{ns}	1.14^{ns}	3.06*	0.143*	0.102^{ns}	0.101^{ns}	0.265^{ns}
N rate effect for S_{Ret}								
0 mean	28.33a	31.47a	29.33a	89.13a	2.382a	2.699a	2.536a	7.617a
50 mean	29.58a	32.62a	29.99a	92.19a	2.492a	2.778a	2.657a	7.836a
100 mean	29.46a	32.26a	29.31a	91.03a	2.485a	2.766a	2.495a	7.745a
$LSD_{0.05}$	1.66^{ns}	1.61^{ns}	1.65^{ns}	4.28^{ns}	0.146^{ns}	0.123^{ns}	0.129^{ns}	0.328^{ns}

Asterisk and ns refer to significant treatment effects in ANOVA at $P \leq 0.05$ and not significant, respectively

[a] *ZT* zero tillage, *CT* conventional tillage, S_{Rem} straw removed, S_{Ret} straw retained, 0, 50 and 100 kg N ha^{-1}

[b] Also named Residual Mean Square (RMS). All ANOVA values from the ANOVA table, not presented

[c] The difference between two means followed by the same letter is not statistically significant at $P \leq 0.05$

showed trends similar to LFOC mass, and it increased by 30.2 kg N ha^{-1} with application of 100 kg N ha^{-1} and by 16.1 kg N ha^{-1} with straw retention in the 0–15 cm soil layer (Table 4).

Spring 2007 soil samples

There was a significant effect of tillage on LFOC mass in the 5–10 and 0–15 cm soil layers, and on LFON mass in the 5–10, 10–15 and 0–15 cm soil layers (Table 5). In the 0–15 cm soil layer, the mass of LFOC and LFON was higher under CT than ZT (by 451 kg C ha^{-1} for LFOC and by 25.3 kg N ha^{-1} for LFON). There was a significant effect of N application on LFOC mass in the 0–5 and 0–15 cm soil layers, and on LFON mass in the 0–5, 10–15 and 0–15 cm soil layers. In the 0–15 cm soil layer, LFOC due to N fertilizer application was increased by 388 kg C ha^{-1} at the 50 kg N ha^{-1}, and by 517 kg C ha^{-1} at the 100 kg N ha^{-1} rate. The increase for LFON was 36.0 kg N ha^{-1} at both the 50 kg and 100 kg N ha^{-1} rates. The mass of LFOC and LFON in the 0–15 cm soil layer tended to be higher (by 285 kg C ha^{-1} for LFOC and by 12.6 kg N ha^{-1} for LFON, but not

Table 4 Effect of long-term tillage, straw and N rate on mass of light fraction organic C (LFOC) and N (LFON) in soil in autumn 1998 at Ellerslie, Alberta, Canada (Black Chernozem soil, experiment established in autumn 1979)

Treatment[a] (tillage/straw/kg N ha^{-1})	LFOC mass (kg C ha^{-1}) in soil layers (cm)			LFON mass (kg N ha^{-1}) in soil layers (cm)		
	0–7.5	7.5–15	0–15	0–7.5	7.5–15	0–15
Treatment effect						
$ZTS_{Rem}0$	1,114	485	1,599	55.3	20.1	75.4
$ZTS_{Ret}0$	1,238	442	1,679	67.0	20.4	87.4
$ZTS_{Ret}50$	1,240	460	1,700	64.0	22.1	86.1
$ZTS_{Ret}100$	1,740	483	2,223	95.2	21.8	117.0
$CTS_{Rem}0$	908	467	1,375	46.7	22.2	67.8
$CTS_{Ret}0$	1,313	510	1,824	63.2	24.7	87.9
$CTS_{Ret}50$	1,750	458	2,226	90.7	24.3	115.0
$CTS_{Ret}100$	1,634	593	2,208	87.4	31.5	118.8
ANOVA						
F-test value	2.86	0.75	2.89	3.76	2.04	4.84
F-test probability *P*	0.0293	0.6364	0.0280	0.0086	0.977	0.0022
Error mean squares (EMS)[b]	13,3429.3	12,071.6	14,8341.4	343.460	26.1403	325.238
Tillage effect						
ZT mean[c]	1,333a	467a	1,800a	70.4a	21.1a	91.5a
CT mean	1,401a	507a	1,908a	71.7a	25.6b	97.4a
$LSD_{0.05}$	325^{ns}	77^{ns}	343^{ns}	17.8^{ns}	3.8*	18.5^{ns}
Straw effect at 0 N						
S_{Rem} mean	1,011a	476a	1,487a	50.5a	21.1a	71.6a
S_{Ret} mean	1,275a	476a	1,752a	65.1a	22.5a	87.7a
$LSD_{0.05}$	426^{ns}	98^{ns}	486^{ns}	21.5^{ns}	5.4^{ns}	22.6^{ns}
N rate effect for S_{Ret}						
0 mean	1,275a	476a	1,752a	65.1a	22.5a	87.7a
50 mean	1,495ab	459a	1,954ab	77.4ab	23.2a	100.6ab
100 mean	1,687b	538a	2,225b	91.3b	26.6a	117.9b
$LSD_{0.05}$	352*	109^{ns}	340*	18.9*	6.6^{ns}	17.7**

Asterisks and ns refer to significant treatment effects in ANOVA at $P \leq 0.05$, $P \leq 0.01$ and not significant, respectively

[a] *ZT* zero tillage, *CT* conventional tillage, S_{Rem} straw removed, S_{Ret} straw retained, 0, 50 and 100 kg N ha^{-1}

[b] Also named Residual Mean Square (RMS). All ANOVA values from the ANOVA table, not presented

[c] The difference between two means followed by the same letter is not statistically significant at $P \leq 0.05$

significant) in the S_{Ret} than S_{Rem} treatments. The responses of LFOC and LFON to straw management and N fertilizer treatments were much more pronounced in the surface 0–5 cm soil layer, but to tillage in the deeper soil layers.

C:N ratios in various organic fractions

The treatment effects on C:N ratios in the 0–15 cm soil layer were significant only for light organic fractions (data not shown). Tillage and straw management had no effect on C:N ratios in most cases (23.68) than ZT (22.07). The C:N ratios in light organic fractions significantly decreased with increasing N rate (from 20.06 at zero-N to 18.91 at 100 kg N ha^{-1}). The C:N ratios were much higher for light organic fractions (range of 18.81 to 20.93) than the total organic fractions (range of 11.22 to 11.43). This was most likely due to higher concentration of organic C in freshly decomposing crop residues for the light organic fraction than the total organic matter.

Table 5 Effect of long-term tillage, straw and N rate on mass of light fraction organic C (LFOC) and light fraction organic N (LFON) in soil in spring 2007 at Ellerslie, Alberta, Canada (Black Chernozem soil, experiment established in autumn 1979)

Treatment[a] (tillage/straw/kg N ha^{-1})	LFOC (kg C ha^{-1}) at soil depths (cm)				LFON (kg N ha^{-1}) at soil depths (cm)			
	0–5	5–10	10–15	0–15	0–5	5–10	10–15	0–15
Treatment effect								
$ZTS_{Rem}0$	744	309	224	1,277	38.8	12.8	7.5	59.0
$ZTS_{Ret}0$	1,032	267	225	1,523	48.6	10.9	7.9	67.3
$ZTS_{Ret}50$	1,408	360	237	2,004	69.1	15.9	9.0	94.0
$ZTS_{Ret}100$	1,295	349	241	1,886	68.4	15.4	9.9	93.7
$CTS_{Rem}0$	776	510	223	1,508	34.2	24.8	9.4	68.4
$CTS_{Ret}0$	952	665	215	1,831	44.7	31.8	8.8	85.2
$CTS_{Ret}50$	1,395	963	292	2,650	69.9	48.8	11.9	130.6
$CTS_{Ret}100$	1,354	894	256	2,503	70.6	47.6	12.8	131.0
ANOVA								
F-test value	4.42	18.76	0.98	10.33	5.49	17.73	2.62	11.29
F-test probability *P*	0.0037	0.0001	0.4690	0.0001	0.0011	0.0001	0.0409	0.0001
Error mean squares (EMS)[b]	6,9712.1	15,767.9	25,53.9	89,868.9	175.27	52.770	5.1717	268.46
Tillage effect								
ZT mean[c]	1,120a	321a	232a	1,672a	56.2a	13.8a	8.6a	78.5a
CT mean	1,119a	758b	247a	2,123b	54.9a	38.2b	10.6b	103.8b
$LSD_{0.05}$	257[ns]	131***	37[ns]	363*	14.2[ns]	7.5***	1.8*	20.6*
Straw effect at 0 N								
S_{Rem} mean	760a	409a	223a	1,392a	36.5a	18.8a	8.4a	63.7a
S_{Ret} mean	992a	466a	220a	1,677a	46.7a	21.3a	8.3a	76.3a
$LSD_{0.05}$	271[ns]	218[ns]	50[ns]	344[ns]	12.8[ns]	12.0[ns]	2.1[ns]	16.6[ns]
N rate effect for S_{Ret}								
0 mean	992a	466a	220a	1,677a	46.7a	21.3a	8.3a	76.3a
50 mean	1,140ab	661a	264a	2,065ab	69.5b	32.3a	10.4ab	112.3b
100 mean	1,324b	621a	249a	2,194b	69.5b	31.5a	11.3b	112.3b
$LSD_{0.05}$	294*	345[ns]	51[ns]	466*	14.7**	19.3[ns]	2.6*	26.4*

[a] *ZT* zero tillage, *CT* conventional tillage, S_{Rem} straw removed, S_{Ret} straw retained, 0, 50 and 100 kg N ha^{-1}

[b] Also named Residual Mean Square (RMS). All ANOVA values from the ANOVA table, not presented

[c] The difference between two means followed by the same letter is not statistically significant at $P \leq 0.05$

Asterisks and ns refer to significant treatment effects in ANOVA at $P \leq 0.05$, $P \leq 0.01$, $P \leq 0.001$ and not significant, respectively

Relationships among the soil organic C and N fractions, and between the crop residue or C input and soil organic C or N fractions

There were generally strong and highly significant positive correlations among TOC, TON, LFOC and LFON, although the correlations between TON and LFOC or LFON, and between TOC and LFON were not significant for the 2007 soil samples (Table 6). The cumulative crop residue C inputs in various treatments for growing seasons from 1980 to 1998, and from 1980 to 2006 (Table 1) usually had highly significant positive correlations with TOC, TON, LFOC and LFON (Table 6). Linear regressions between crop residue C input and soil organic C or N fractions are presented in Table 7, and the R^2 values were fairly high and significant in most cases.

Discussion

Soil biochemical properties

Tillage, by incorporating crop surface residues into the soil, increases their oxidation/decomposition (Doran

Table 6 Relationships among soil organic C or N fractions (TOC, TON, LFOC and LFON), or between crop residue C input from 1980 to 1998 or 2006 growing seasons and soil organic C or N stored in soil sampled in autumn 1998 and in spring 2007at Ellerslie, Alberta, Canada (Black Chernozem soil, experiment established in autumn, 1979)

Parameter	Correlation coefficients			
	TOC	TON	LFOC	LFON
Relationships among soil organic C or N fractions				
1998 soil samples				
TOC		0.979***	0.759*	0.753*
TON			0.867**	0.863**
LFOC				0.988***
2007 soil samples	TOC	TON	LFOC	LFON
TOC		0.991***	0.699*	0.675 ^{ns}
TON			0.633 ^{ns}	0.610 ^{ns}
LFOC				0.992***
Relationships between crop residue C input and soil organic C or N fractions				
1980 to 1998	0.776*	0.865**	0.871**	0.890**
1980 to 2006	0.895**	0.845**	0.876**	0.876**

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

Table 7 Linear regressions for relationships between crop residue C input from 1980 to 1998 or 2006 growing seasons and soil organic C or N (TOC, TON, LFOC and LFON) stored in soil sampled in autumn 1998 and in spring 2007at Ellerslie, Alberta, Canada (Black Chernozem soil, experiment established in autumn, 1979)

Crop residue C parameter (X) in years	Soil C or N parameter (Y)	[z]Linear regression ($Y = a + bX$)	R^2
1980 to 1998	TOC	$Y = 90.74 + 0.1451X$	0.602*
	TON	$Y = 7.897 + 0.0136X$	0.749**
	LFOC	$Y = 1325.7 + 18.99X$	0.759**
	LFON	$Y = 61.68 + 1.1766X$	0.792**
1980 to 2006	TOC	$Y = 84.73 + 0.1197X$	0.801**
	TON	$Y = 7.306 + 0.0084X$	0.713**
	LFOC	$Y = 1103.5 + 19.91X$	0.770**
	LFON	$Y = 45.85 + 1.1354X$	0.767**

* and ** refer to significant treatment effects in ANOVA at $P \leq 0.05$ and $P \leq 0.01$, respectively

1980; Doran and Scott-Smith 1987). Thus, a substantial increase in the organic C in soil is expected under ZT compared to CT (Halvorson et al. 2002). However, in our study for 19 or 27 years, there was only a small increase in mass of TOC and TON in soil under ZT compared to CT (1.18 Mg C ha^{-1} and 0.116 Mg N ha^{-1}, significant only in the 0–5 cm soil layer in 2007). The large amount of initial organic C in soil may have resulted in the small difference in soil organic C and N between ZT and CT. Similarly after 11 years, Nyborg et al. (1995) did not find any significant increase in TOC and TON in the soil due to ZT at Ellerslie (Black Chernozem with high organic C content), but found a significant increase in organic C in the soil at Breton (Gray Luvisol with low organic C content). The initial concentration of TOC at Ellerslie was 56.45 g C kg^{-1} compared to 13.75 g C kg^{-1} at Breton. Other researchers have also suggested that soil organic C changes in response to C input and other management practices are dependent on the initial C content of soil (Hassink and Whitmore 1997; Thomson et al. 2006; Gulde et al. 2008). Thus, there is apparently less C sequestration and storage in soils with a high initial organic C compared to soils with low initial organic C content. This also suggests that soils inherently rich in organic C are apparently much slower in their response to change in soil quality due to management practices than low organic C soils.

In the Canadian prairies, research has shown an increase in organic C and/or N from N fertilization (Janzen et al. 1998; Malhi and Lemke 2007). This was attributed to the increase in crop yield with N fertilization, and the subsequent return of more organic C and/or N to the soil through crop residue including straw, chaff (Campbell et al. 1991; Nyborg et al. 1995; Malhi and Lemke 2007) and root (Malhi and Gill 2002). Similarly, there was an increase in TOC (3.06 Mg C ha^{-1}) and TON (0.219 Mg N ha^{-1}) in soil due to N fertilization (50 kg N ha^{-1}) at our experimental site after 27 growing seasons. However, the increase was considered small in spite of good crop yield response to applied N, most likely because of high initial organic C content in this soil, as explained earlier. Any increase in TON in soil would suggest improvement in N supplying power of soil in future years for sustainable productivity (Izaurralde et al. 2001).

Because crop residues are a source of organic matter in soil, retaining crop residues in the field is expected to increase organic C and N storage in soil, whereas their removal can result in substantial loss of organic C and N from the system (Nuttall et al. 1986; Campbell et al. 1991, 1998; Nyborg et al. 1995; Solberg et al. 1997; Malhi and Lemke 2007). In our study, the mass of TOC and TON in the 0–15 cm soil layer was higher when straw was retained than when it was removed (3.44 Mg C ha^{-1} and 0.248 Mg N ha^{-1}, Table 3). The increase in organic C and N in soil by the S_{Ret} treatment was most likely associated with the amount of above-ground and below-ground crop residues returned to the soil, as suggested by other researchers (Campbell et al. 1991, 1998; Nyborg et al. 1995). The lower mass of C and N in soil when straw was removed than when it was retained suggests that the practice of removing straw from fields for on-farm and industrial uses, or to facilitate convenient seeding operations, may in the long run result in soil degradation or deterioration of soil physical, chemical or biological properties including the N-supplying power of soil, especially under CT (Campbell et al. 1998; Izaurralde et al. 2001; Singh and Malhi 2006). In the present study, the comparisons between S_{Rem} and S_{Ret} treatments were made at the zero-N rate, and differences in organic C and N might be greater if N fertilizer was also used in S_{Rem} treatments.

The total amount of organic C stored in the soil is the difference between C input (crop residues) and C output (C loss through gases arising from decomposition of crop residues plus soil erosion). Due to the additive effects of soil, crop residue and fertilizer management practices on C sequestration, one would expect a dramatic increase in organic C in soil from a combination of ZT, straw retention and fertilization. In our study, TOC and TON in soil increased with elimination of tillage, straw retention and N fertilization, but apparently the mass of TOC and TON in different soil layers was not always the highest in the $ZTS_{Ret}100$ treatment.

Earlier research has shown that LFOC and LFON are more responsive to management practices than TOC and TON (Bremer et al. 1995; Solberg et al. 1997; Malhi et al. 2003a, b, c; Malhi and Lemke 2007). Therefore, monitoring of the changes in LFOC and LFON in the surface soil appears to be a good strategy to determine the potential N supplying power, and improvement in soil quality/health. In our study, the changes of organic C and N in the light organic fractions were relatively greater than the total organic fractions in the S_{Ret} treatment with applied N under both ZT and CT, and this was most likely due to recent additions of greater input of C and N to soil through straw and chaff in the S_{Ret} treatment (Malhi and Lemke 2007) plus increased root mass from fertilization (Malhi and Gill 2002). Lower amounts of C and N in the light organic fractions in soil in S_{Rem} than S_{Ret} treatment suggest that the practice of straw removal to facilitate seeding (or for livestock or industrial purposes) may degrade/deteriorate soil quality over the long term (Dalal 1992). Due to reduced loss of organic C and N from decomposition/mineralization of crop residues through elimination of tillage (Doran 1980; Doran and Scott-Smith 1987), one would expect greater accumulation/storage of LFOM in soils under ZT than CT. However, the LFOC and LFON in the 5–10 and 10–15 cm soil layers were higher under CT than ZT. It could be that large amounts of straw and other crop residue buried deep in the soil under CT decomposed relatively slower, resulting in higher LFOC and LFON under CT than ZT in the 0–15 cm soil layer in both the 1998 and the 2007 samples. Overall, our findings suggest that even after 27 years, the effect of tillage management on soil organic C and N is weak, and that the stronger effects on organic C and N storage in soil come from straw retention and N fertilization on this soil inherently rich in organic matter.

Historical comparisons of TOC concentration in soil

Among the four treatments that did not receive N fertilizer ($ZTS_{Rem}0$, $ZTS_{Ret}0$, $CTS_{Rem}0$ and $CTS_{Ret}0$), $ZTS_{Ret}0$ showed slight increase in TOC concentration in the 0–15 cm soil layer in the first 19 years, and then slight decrease in the last 8 years, while $CTS_{Ret}0$ treatment kept TOC concentration unchanged over the over time from autumn 1979 to spring 2007 (Fig. 1a). Both $ZTS_{Rem}0$ and $CTS_{Rem}0$ treatments showed a dramatic decrease in TOC concentration over the first 11 years of the experiment and then increase in TOC from autumn 1990 to autumn 1998, with much larger increase in the $ZTS_{Rem}0$ treatment. Since then $ZTS_{Rem}0$ showed essentially no change in TOC, while $CTS_{Rem}0$ continued to increase TOC but TOC concentration was still lower than $ZTS_{Rem}0$ treatment. At the end of 27 years, TOC concentration in soil was in the order of $ZTS_{Ret}0 > CTS_{Ret}0 > ZTS_{Rem}0 > CTS_{Ret}0$.

Considering only the ZT treatments, $ZTS_{Rem}0$ resulted in a substantial loss in TOC concentration in the 0–15 cm soil layer in the first 11 years of the experiment, and then increase in the following 8 years and little change in the last 8 years, with a net loss in TOC in spring 2007 compared to autumn 1979 (Fig. 1b). The $ZTS_{Ret}0$ treatment showed slight increase in TOC concentration in the first 19 years and then slight decrease in the last 8 years, with only slight gain in TOC after 27 years. The other two treatments usually had a positive effect, with higher increase under $ZTS_{Ret}100$ than $ZTS_{Ret}50$. The TOC concentrations in soil after 27 years in the four ZT treatments were in the order of $ZTS_{Ret}100 > ZTS_{Ret}50 > ZTS_{Ret}0 > ZTS_{Rem}0$.

Like ZT treatments, $CTS_{Rem}0$ showed considerable decrease in TOC concentration in the 0–15 cm soil layer in the first 11 years of the experiment, and then increase in the following 16 years, but still with a net loss in TOC in spring 2007 compared to autumn 1979 (Fig. 1c). The $CTS_{Ret}0$ treatment showed very little changes in TOC concentration over the 27 years. The other two treatments had a steady increase in TOC in soil from autumn 1979 to spring 2007, but the increase was relatively higher under $ZTS_{Ret}50$ than $ZTS_{Ret}100$, and we do not have any explanation for this trend.

Overall, in treatments that did not receive any N fertilizer ($CTS_{Rem}0$, $CTS_{Ret}0$, $ZTS_{Rem}0$ and $ZTS_{Ret}0$), $CTS_{Rem}0$ resulted in a net decrease in TOC concentration (by 1.9 g C kg^{-1}), while there was a net increase in TOC concentration (by 1.2 g C kg^{-1}) in the $ZTS_{Ret}0$ treatment in the 0–15 cm soil layer in 2007 (after 27 years) compared to the 1979 results at initiation of the experiment (Fig. 1a). There as little or no change in TOC concentration in the $CTS_{Ret}0$ and $ZTS_{Rem}0$ treatments. Straw retention and N fertilizer application at 50 and 100 kg N ha^{-1} rates showed net positive effects on TOC concentration under both ZT and CT in 2007 compared to 1979 data (Fig. 1b, c). The net increase in TOC concentration was by 2.3 g C kg^{-1} in $ZTS_{Ret}50$, by 3.1 g C kg^{-1} in $ZTS_{Ret}100$, by 3.5 g C kg^{-1} in $CTS_{Ret}50$, and by 1.6 g C kg^{-1} in $CTS_{Ret}100$ treatments.

Lower concentration of soil TOC over years in the zero-N treatments under CT compared to ZT was most likely due to a tillage effect, because tillage makes crop residues more accessible to soil microorganisms by incorporating them into soil, and subsequently results in faster oxidation/decomposition of organic matter. The highest decrease of soil TOC under CT in the $CTS_{Rem}0$ treatment was due to removal of straw (with little input of crop residue as a source of organic matter) as suggested by Campbell et al. 1991, plus tillage resulting in oxidation of native soil organic matter in this treatment as suggested by Doran (1980) and Doran and Scott-Smith (1987). Compared to the $CTS_{Ret}0$ treatment, the increase in TOC between 1979 and 2007 in $CTS_{Ret}50$ and $CTS_{Ret}100$ treatments was probably due to the return of more crop residue from increased crop growth/yield and increased root mass with applied N fertilizer, as suggested by other researchers (Lorenz 1977; Malhi and Gill 2002). In the $ZTS_{Rem}0$ treatment, the loss of TOC in soil was most likely due to removal of crop residue.

Previous research has indicated increase in the concentration of soil TOC with inputs of straw compared to when straw was removed (Nyborg et al. 1995). Similarly, in our present study, soil TOC was increased in fertilized treatments when

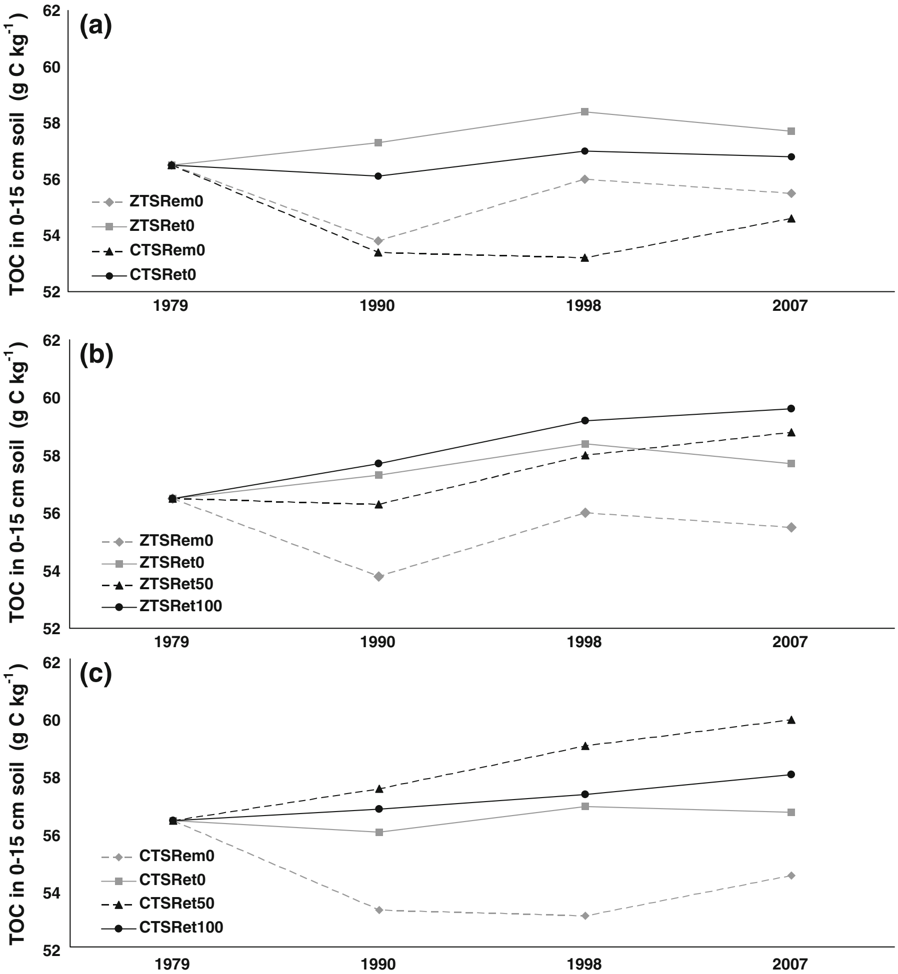

Fig. 1 Historical comparisons of total organic C (TOC) concentration in 0–15 cm soil in 1979, 1990, 1998 and spring 2007 for each treatment at Ellerslie, Alberta, Canada (Black Chernozem soil, experiment established in autumn 1979—mean total organic C concentration was 56.45 g C kg^{-1} in 1979). *ZT* zero tillage, *CT* conventional tillage, S_{Rem} straw removed, S_{Ret} straw retained, 0, 50 and 100 kg N ha^{-1}. **a** Comparing TOC for $ZTS_{Rem}0$, $ZTS_{Ret}0$, $CTS_{Rem}0$ and $CTS_{Ret}0$ treatments; **b** Comparing TOC for $ZTS_{Rem}0$, $ZTS_{Ret}0$, $ZTS_{Ret}50$ and $ZTS_{Ret}100$ treatments; and **c** Comparing TOC for $CTS_{Rem}0$, $CTS_{Ret}0$, $CTS_{Ret}50$ and $CTS_{Ret}100$ treatments

straw was retained. Compared to the $ZTS_{Rem}0$ treatment, the decrease in TOC concentration was relatively greater in the $CTS_{Rem}0$ treatment because of tillage, which may have caused oxidation of organic C. Compared to the $ZTS_{Ret}0$ treatment, the relative decrease in TOC concentration was much greater in the $CTS_{Rem}0$ treatment, possibly because of the combined effect of tillage resulting in oxidation of organic C, plus smaller addition of crop residue due to removal of straw in this treatment. In addition to high initial organic C concentration of this soil, the lack of continuous positive changes in TOC after 1998 was probably because the soil at this site may have reached a new steady state (annual cropping of mostly coarse grains). Bremer et al. (1995) suggested that the time to reach a new steady state after a change in management ranges from 10 to 20 years. Therefore, without a change in management practices in our study, further increases in C or N could not be detected.

Additional potential benefits and implications of our findings

Based on the findings of our and other previous research in the Parkland region of western Canada, this is speculated that the improvement in organic C and N in soil due to tillage, crop residue, or N fertilizer management practices in the present study can have additional potential benefits/implications with respect to conservation agriculture in the Canadian prairies. For example, the improvement in soil aggregation to minimize crusting of soil at the surface and thus improve seedbed quality and reduce soil erosion potential, increase in soil moisture conservation/storage by trapping more snow and reducing evaporation through standing stubble and straw mulching, as well as enhancing macro organic matter and nutrient supplying power of soil to supply balanced plant nutrients (Nyborg and Malhi 1989; Malhi and O'Sullivan 1990; Singh et al. 1994, 1996; Malhi et al. 2006, 2009, 2010; Singh and Malhi 2006; Malhi and Lemke 2007), and all these subsequently/consequently may result in increased sustainability of crop production over years, especially in relatively drier years. The quality of seedbed is closely related to soil aggregation (Braunack and Dexter 1989), and also soil has better structure and aggregate stability when tillage is eliminated and crop residue is returned to the field (Tisdall and Oades 1980; Singh and Malhi 2006; Malhi et al. 2009). Soil aggregate size distribution and stability may increase porosity, promote bio-channels (e.g., earthworms) and thus affect water infiltration, runoff and drainage properties (Singh et al. 1994, 1996), and these are also linked to increase in soil organic C storage, especially recently added C such as LFOC. In our study, LFOC improved with S_{Ret}, suggesting that retaining crop residue in the field can reduce the potential for soil erosion, as suggested by Singh and Malhi (2006). Our findings also indicate that N fertilization can be used to sequester more atmospheric C in soil organic matter, especially in light fraction, and also suggest that the process of improvement in soil quality can be accelerated with appropriate fertilization. In our study, the majority of the increase in soil organic C due to N fertilization occurred in the light fraction form. Since the light fraction is a labile fraction and LFOM decomposes faster in soil than total organic matter (Sollins et al. 1984; Dalal and Mayer 1986; Bonde et al. 1992), the stored organic C in soil can be readily lost if management practices are changed in future, such as removal of straw for on-farm (animal feed) and off-farm (industrial cardboard/paper, fuel) uses, and discontinuation of N fertilization or reverting to conventional tillage by switching to organic crop production systems (where chemicals are not allowed and land is normally tilled). As soil organic matter is a source of nutrients for plants (Carter et al. 1994), and food for microorganisms for high microbial populations/diversity, enzyme activity and soil respiration (Kanazawa and Philip 1986; Janzen et al. 1992), faster decomposition of LFOM due to new/altered management practices could be useful to supply plant nutrients including nitrate–N, but enhanced microbial activity/soil respiration may increase the potential for nitrate–N loss and nitrous oxide (N_2O-N) greenhouse gas (GHG) emissions, and this may not be good for the environment and for long-term sustainability of soil quality/health/productivity (Malhi et al. 2006; Malhi and Lemke 2007).

Conclusions

The mass of TOC and TON in soil was usually higher in S_{Ret} than in S_{Rem} treatment, but there was little effect of elimination of tillage and N fertilizer application on these parameters. The mass of LFOC and LFON in soil tended to increase with straw retention and N fertilization, but was higher under CT than ZT. In conclusion, the increases in organic C and N storage in soil were mainly associated with retention of straw and N fertilization, and mass of organic C and N in soil was usually lowest when straw was removed and no N fertilizer was applied, especially under CT.

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