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Crop rotation and tillage impact on carbon sequestration in Canadian prairie soils

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Abstract

Carbon sequestration was determined for different tillage systems in semiarid to sub-humid climates and coarse to fine-soil texture in Saskatchewan, Canada. Annually cropped rotations sequestered 27–430 kg C ha^{-1} per year more than crop rotations containing bare fallow. The potential for sequestering soil organic C (SOC) with crop rotations without bare fallow was greater in the sub-humid than in the drier climates. No-tillage (NT) sequestered 67–512 kg C ha^{-1} per year more than tilled systems. With elimination of both tillage and bare fallow, the SOC increase was approximately 300 kg C ha^{-1} per year in the semiarid climate regardless of soil texture, and approximately 800 kg C ha^{-1} per year in the sub-humid climate. Relative annual increase in SOC under no-till was approximately a linear function of clay content across locations. Fine-textured soils have a greater potential for gains in SOC under no-till in Canadian prairie region.

Keywords: C sequestration; Tillage; Crop rotation; Soil texture

1. Introduction

Agricultural soil is a source and a sink of atmospheric CO_2. Management practices that promote sequestration of C as soil organic C (SOC) will remove CO_2 from the atmosphere. The amount of SOC is a function of net primary production and rate of decomposition of SOC. No-tillage (NT) has been known to sequester SOC compared with cultivator tillage (CT), especially within the top 5- or 10-cm soil (Campbell et al., 1995, 1996a,b). Since differences in primary crop productivity between CT and NT are generally not pronounced (McConkey et al., 1996), C sequestration under NT is believed to result from reduced decomposition of SOC because of less aerobic environment (Doran, 1980) and better physical protection of SOC within aggregates (Beare et al., 1994; Balesdent et al., 2000).

Soil texture is known to affect both the amount of SOC and the retention of organic matter from crop

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residues. Linear correlations were found between soil texture and the SOC (Spain, 1990; Hassink, 1994). Added of crop residues decompose more rapidly in sandy soils than in clay soils (Sörensen, 1981; Ladd et al., 1985). With the same input of organic material, clay soils usually contain more organic matter than sandy soils (Jenkinson, 1988). Differences in decomposition rates and amounts of SOC in various textured soils have been attributed to differences in physical protection of SOC. The stabilizing effect has been ascribed to adsorption of organics onto surfaces such as clays (Oades, 1989) and encapsulation between clay particles (Tisdall and Oades, 1982; Elliott and Coleman, 1988). Liang et al. (1998) reported that soil texture directly controls the proportion of crop residue C retained in the soil. Other work has confirmed that aggregation and texture indirectly determine the level of C retained in soil by suppressing biological activity (Hassink, 1996). Reduced tillage can improve soil aggregation and reduce losses of SOC that result from cultivation (Havlin et al., 1990; Carter, 1992; Weill et al., 1989).

Recent research suggest that gains in SOC after adoption of NT increase with clay content (Campbell et al., 1996a). In semiarid southwestern Saskatchewan, Canada, Campbell et al. (1995, 1996a,b) reported that NT gained from 0.5 to 5 Mg ha^{-1} more C than CT in the 0–15 cm soil within 11 or 12 years, and the magnitude of SOC increase was related to soil clay content. However, because of variations in the duration of experiments and limited number of soil types reported by Campbell et al. (1995, 1996a,b) it is not clear whether these increases in SOC under NT were quantitatively related to soil texture. This information may be important for providing a quantitative measure of C sequestration under NT for Canadian prairie soils. The objectives of this study were (1) to quantify the impact of crop rotations and tillage on C sequestration, and (2) to quantify the impact of soil texture on C increase under NT in six Saskatchewan soils.

2. Materials and methods

The six experiments involved a range of climates, soil textures, crop rotations, and tillage systems (Table 1). Based on general moisture regime, we divided the sites into semiarid (Hatton fine sandy loam, Swinton silt loam, and Sceptre clay) and sub-humid (Elstow loam, Indian Head clay, and Melfort silty clay loam). All of these studies were originally designed to compare the agronomic performance of tillage systems. Common to all experiments was relatively large plot size (350–1400 m^2), so full-size farm equipment was used for tillage and planting. Also common was tillage depth of 5–7 cm. All experiments received N and P fertilizer to remove nutrient stress for average crop production levels. Finally, common to all experiments was that in-crop herbicides were used in all systems, as required to control weeds.

Experimental design, the spring wheat (*Triticum aestivum* L.) rotations and tillage practices were similar for the Swinton silt loam (SiL), Sceptre clay (C) and Hatton fine sandy loam (FSL). Experimental details that are relevant to this study are briefly described. Other details of management of these experiments are reported elsewhere (Campbell et al., 1995, 1996a,b). Two crop rotations, continuous wheat (Cont W) and fallow-wheat (F-W) were used. Each phase of F-W, the fallow phase ((F)-W) and the wheat phase (F-(W)) was presented each year. Tillage systems for these studies consisted of minimum tillage (MT) and NT. Pre-seeding tillage with one operation of heavy-duty cultivator equipped with sweeps and rodweeder, or mounted harrow, was used for MT. For NT, weeds were controlled before planting with herbicides. NT fallow involved herbicides only while MT fallow used one application of broad-spectrum herbicides plus one or two operations with wide-blade cultivator and/or heavy-duty cultivator. A combination of insect damage and dry weather conditions produced severe wind erosion for MT in 1984 on the Hatton FSL (losing approximately 5 cm of soil), so NT was used on the fallow phase of MT F-W until 1988, when there was adequate residue to control erosion. Planting was performed with an offset disc press drill (Dyck and Tessier, 1986) for NT and a conventional hoe drill for MT.

On the Melfort silty clay loam (SiCL), three tillage systems (CT, MT and NT) under a F-W rotation were used. Each phase of the rotation was present each year. A heavy-duty cultivator equipped with sweeps was used for tillage operations on summer-fallow; in some years a rodweeder replaced one or more of the cultivation operations. The first fallow tillage operation was performed usually in early June with subsequent three to seven tillage operations performed on an

Table 1
Soil types, locations, climate, duration of tillage experiments until SOC measured, soil texture, crop rotations, and tillage systems in six mid- to long-term tillage experiments in Saskatchewan

Soil	FAO soil classification	Location	Mean annual			Years after initiation (year)	Soil texture		Crop rotation[a]	Tillage system[b]
			Precipitation (mm)	Air temperature (°C)	Moisture deficit[c] (mm)		Sand (%)	Clay (%)		
Hatton fine sandy loam	Haplic Kastanozem[d]	50°24′N, 108°00′W	334	3.3	400	11	70.8	15.3	Cont W, F-(W), (F)-W	MT, NT
Swinton silt loam	Haplic Kastanozem[d]	50°16′N, 107°44′W	334	3.3	400	12	32.6	27.6	Cont W, F-(W), (F)-W	MT, NT
Sceptre clay	Vertic Kastanozem[e]	50°36′N, 107°48′W	334	3.3	400	11	25.7	42.7	Cont W, F-(W), (F)-W	MT, NT
Elstow clay loam	Haplic Kastanozem[d]	52°22′N, 108°50′W	355	1.0	270	16	29	31.0	WW(C)WWX, FXWFCW,	CT, NT
Indian Head clay	Vertic Chernozem[e]	50°32′N, 103°40′W	427	2.0	150	8	16.3	63.1	WWXwW, PSXwW, FWWwW	CT, MT, NT
Melfort silty clay loam	Vertic Chernozem[f]	52°51′N, 104°37′W	411	0.3	150	25	16.0	44.0	F-(W)	CT, MT, NT

[a] Letters in the parenthesis indicate the rotation phase sampled, W: spring wheat, F: fallow, X: flax, wW: winter wheat, P: pea, C: canola.

[b] CT: cultivator tillage (full tillage after crop, preseeding tillage, tillage as required for weed control during fallow); MT: minimum tillage preseeding tillage, herbicides and tillage used for weed control during fallow); NT: no-tillage (low disturbance direct seeding, all weed control with herbicides).

[c] Potential evaporation minus mean annual precipitation (Campbell et al., 1990).

[d] Typic Haplustoll.

[e] Vertic Haplustoll.

[f] Vertic Haplocryoll.

as-needed basis usually at 2–3-week intervals. Treatments of NT for weed control during fallow generally received a first herbicide application in late May or early June with repeat applications as required usually in July and August. Tillage operation for MT was similar to that of CT, but the number of tillage operation was reduced to twice a year by substituting herbicides for some weed control. From 1969 to 1976, all tillage systems including NT received tillage before seeding (Zentner et al., 1990), thereafter only the CT and MT systems received pre-seeding tillage. Other details of the experiment are reported (Zentner et al., 1990).

On the Indian Head clay (C), crop systems consisted of three, 4-year rotations. One crop rotation included 1 year of fallow in four, fallow–spring wheat–spring wheat–winter wheat (FWWwW) while the other crop rotations were continuous cropping systems, pea (*Pisum sativum* L.)–spring wheat–flax (*Linum usitatissum* L.)–winter wheat (PWXwW) and spring wheat–spring wheat–flax–winter wheat (WWXwW) (Lafond et al., 1992). Each phase of each rotation was present each year. Three tillage systems (CT, MT and NT) were used. MT included only one tillage operation in the spring using a heavy-duty cultivator equipped with 41 cm sweeps. CT included fall tillage after harvest and spring tillage before seeding. In the NT system, weeds on fallow were controlled with herbicide applications. In the CT system, weed control on fallow was by mechanical means, with 2–4 cultivations and 0–3 rodweeder operations per year. Weed control on MT fallow was accomplished with herbicides and one operation with heavy-duty cultivator followed by one operation with a rodweeder. Details of the experiment can be found elsewhere (Lafond et al., 1992).

On the Elstow clay loam (CL), two crop rotations including a continuous cropped rotation of wheat–wheat–canola (*Brassica napus* L.)–wheat–wheat–flax (WWCWWX) and a rotation containing one fallow in 3 years, fallow–flax–wheat–fallow–canola–wheat (FXWFCW), were used. Only one phase of WWCWWX was present each year and only three phases of the FXWFCW rotation were present each year. Tillage systems were CT and NT. Herbicides were used exclusively for weed control in the NT treatments. In the CT cropping system, tillage with a heavy-duty cultivator equipped with spikes or sweeps was performed on stubble in late fall. Early spring tillage was carried out with a cultivator equipped with mounted harrows followed by cultivating or rod weeding just prior to planting for all CT treatments. The tillage fallow normally required three operations with a cultivator and mounted harrows, plus one or two operations with a cultivator or rodweeder. Seeders used included a double-disc press drill, an offset double-disc press drill and a narrow hoe press drill. Further experimental detail can be found in Brandt (1992).

In all studies, NT was designed to maximize conservation of crop residue such that there was typically 60–100% soil cover after planting whereas CT had typically 10–40% soil cover after planting. Soil cover with residue after planting under MT was between 20 and 70% cover. For all tillage systems, the least amount of residue within the above ranges would occur the year after fallow, the year after dry year having low crop residue production, or the year after pea or canola that do not produce large persistent crop residue pieces (note straw was chopped and spread during harvesting). Conversely, the maximum residue coverage would occur after cereal crops in years when they produced abundant residue.

Soil samples were taken from 0 to 7.5 cm and 7.5–15 cm depths for the Hatton FSL, Swinton SiL and Sceptre C in the spring of 1994, for the Melfort SiCL and Indian Head C in the fall of 1994, and for the Elstow CL in the fall of 1995. Four soil cores per plot were extracted and composited by depth. The resulting samples were air-dried and sieved through a 2 mm sieve. Crop residues remaining on the sieve were discarded. Representative sub-samples were ground with a rollermill ($<153\,\mu m$) and analyzed for SOC using an automated combustion technique (Carlo Erba™, Milan, Italy). To remove carbonates soil samples were pre-treated with phosphoric acid in a tin capsule after weighing, then drying the sample for 16 h at 75 °C prior to analysis for C. Because of possible changes in soil bulk density (BD) as a result of crop rotations, especially tillage practices, the amount of SOC in the 0–7.5 and 0–15 cm depth was calculated on an equivalent soil mass basis (Ellert and Bettany, 1995). In this calculation procedure, the equivalent soil mass was set to that of the observation with the least mass. Thus, the effective mean depth for calculating SOC mass was less than the stated depth so that all treatments comparisons were for the identical soil mass.

For the Hatton FSL, Swinton SiL and Sceptre C, contrasts were used to separate treatment differences. For these three sites two contrasts were selected to compare crop rotation effect including Cont W versus F-W, and F-(W) versus (F)-W. Only one contrast was selected to compare tillage effect, MT versus NT. For the Melfort SiCL and Elstow CL experimental data were statistically analyzed as one- or two-factor factorial, randomized complete block design, while for the Indian Head C, a split-plot design with tillage in main plots and crop rotations in sub-plots was used. For mean separations, a least significant difference (LSD) was used at $P = 0.05$ level. Regression analysis was used to assess the linear effect of clay content on SOC increases.

All experiments were located on land that had been in long-term CT cereal-based fallow-containing rotations. We defined SOC increase or sequestration for reduction of fallow as the difference between SOC for the continuous cropped rotation and that with fallow-containing rotation and SOC for reduction in tillage as the difference between the SOC under NT and that under MT and/or CT. Since we do not have soil samples or SOC values when experiments were initiated, a key assumption was that all treatments within an experiment had equal initial SOC.

3. Results and discussion

The SOC for the Hatton FSL, Swinton SiL and Sceptre C have been reported previously (Campbell et al., 1995, 1996a,b). In general, there was no interaction effect of crop rotations and tillage on SOC at any site. Thus, tillage and crop rotation effect on SOC will be discussed separately. Where more than one phase of crop rotation was sampled the specific phase of rotation had no impact on SOC in either the 0–7.5 or 0–15 cm soil for the Hatton FSL, Swinton SiL, Sceptre C and Elstow CL (Tables 2 and 3). This was expected because one crop year would not produce any significant change in SOC. However, continuous cropping, compared with fallow-containing rotations, had a higher amount of SOC in the 0–7.5 cm soil for all sites except for the Sceptre C (Tables 2 and 3). This same effect was existed for the 0–15 cm depth of soil

Table 2
Impact of crop rotations on BD and SOC in the Hatton fine sandy loam, Swinton silt loam and Sceptre clay

Crop rotation[a]	Hatton fine sandy loam			Swinton silt loam			Sceptre clay		
	BD	SOC		BD	SOC		BD	SOC	
	$Mg\,m^{-3}$	$mg\,C\,g^{-1}$	$Mg\,C\,ha^{-1}$	$Mg\,m^{-3}$	$mg\,C\,g^{-1}$	$Mg\,C\,ha^{-1}$	$Mg\,m^{-3}$	$mg\,C\,g^{-1}$	$Mg\,C\,ha^{-1}$
	0–7.5 cm								
F-(W)	1.37	8.7	8.1	1.23	15.8	13	1.05	16.3	12.1
(F)-W	1.36	9	8.4	1.24	15.4	12.7	1.12	15.7	11.6
Cont W	1.31	10	9.4	1.17	17.7	14.6	1.13	17.2	12.8
Significant contrast "F-(W) versus (F)-W"	NS[b]	NS	NS	NS	NS	NS	<0.01	NS	NS
Significant contrast "Cont W versus F-W"	<0.01	0.03	0.03	<0.01	<0.01	<0.01	NS	NS	NS
	7.5–15 cm		0–15 cm	7.5–15 cm		0–15 cm	7.5–15 cm		0–15 cm
F-(W)	1.53	7.8	17.2	1.36	14.9	27.1	1.36	14.1	27.1
(F)-W	1.53	9.2	18.9	1.39	14.7	26.9	1.39	13.7	25.7
Cont W	1.53	8.5	19.2	1.35	15.7	29.6	1.43	13.4	26.7
Significant contrast "F-(W) versus (F)-W"	NS	NS	NS	0.02	NS	NS	NS	NS	NS
Significant contrast "Cont W versus F-W"	NS	NS	NS	0.07	NS	<0.01	<0.01	NS	NS

[a] Letters in the parenthesis indicate the rotation phase sampled, W: spring wheat, F: fallow.
[b] Not significant at $P = 0.10$.

Table 3
Impact of crop rotation on BD and SOC in the Elstow clay loam and Indian Head clay

Soil	Crop rotation[a]	BD	SOC[b]	
		$Mg\,m^{-3}$	$mg\,C\,g^{-1}$	$Mg\,C\,ha^{-1}$
		0–7.5 cm		
Elstow clay loam	WWCWWX	1.02	41.2 a	28.8 a
	FXWFCW	1.13	35.5 b	24.9 b
		7.5–15 cm		0–15 cm
	WWCWWX	1.20	35.9 a	57.8 a
	FXWFCW	1.23	32.3 b	50.9 b
Indian Head clay	PWXwW	1.10	32.2 a	21.9 a
	WWXwW	1.09	32.8 a	22.3 a
	FWWwW	1.06	29.9 b	20.4 b
	PWXwW	1.24	23.9 a	43.0 a
	WWXwW	1.29	23.6 a	43.3 a
	FWWwW	1.26	23.1 a	40.4 b

[a] W: spring wheat, F: fallow, X: flax, C: canola, P: pea, wW: winter wheat.

[b] Means followed by the same letters within the same column and the same depth of the same soil are not significantly different at $P = 0.05$ probability level.

for the Swinton SiL, Elstow CL, Indian Head C. Increase in total SOC with continuous cropping varied from 0.3 to 6.9 $Mg\,C\,ha^{-1}$ in the 0–15 cm soil, mainly depending on the duration of experiments and soil type. These increases in SOC were 27 $kg\,C\,ha^{-1}$ per year for the Sceptre C, 110 $kg\,C\,ha^{-1}$ per year for the Hatton FSL, 217 $kg\,C\,ha^{-1}$ per year for the Swinton SiL, 363 $kg\,C\,ha^{-1}$ per year for the Indian Head C, and 430 $kg\,C\,ha^{-1}$ per year for the Elstow CL. A one-way ANOVA showed that SOC increase for reducing fallow in the sub-humid sites was greater than the semiarid sites (analysis not shown). This was despite the fact that continuous cropping represented a smaller decrease in fallow frequency for rotation comparisons in the sub-humid sites than the semiarid sites. Soils in the sub-humid sites also had higher levels of SOC than in the semiarid sites. Greater amounts of SOC sequestered with continuous cropping in the sub-humid sites contradicted with the hypothesis of Janzen et al. (1998), who suggested that the ability to increase SOC would depend not only on the amount of residue C inputs, but also on the C content of the soil at the time of initiation with improved management practices. However, because we do not have SOC at the initiation of NT we cannot determine if the difference between cropping systems is due to increasing SOC with continuous cropping or to decreasing SOC with fallow-containing systems or a combination of both.

Crop rotation effect on BD were only significant for the semiarid sites (Tables 2 and 3). The effect was not consistent as Cont W had lower BD than F-W in the 0–7.5 cm depth at the Hatton FSL and the Swinton SiL sites but, at the Sceptre C site, Cont W had higher BD than F-W in the 7.5–15 cm depth. Generally, the BD was greater under NT than the tilled systems although the difference was only significant for Hatton FSL and Sceptre C sites for the 0–7.5 cm depth and for NT compared with MT for the 7.5–15 cm depth at the Indian Head C site (Tables 4 and 5). The trend of greater BD under NT than the tilled systems would cause reporting of relatively more SOC mass under NT than the tilled systems using a volumetric calculation (data not shown) compared with our reporting using the equivalent soil mass calculation.

Tillage practices had significant impacts on SOC in the 0–7.5 cm soil for all sites (Tables 4 and 5). Increase in SOC under NT in the 0–15 cm soil varied from 0.8 to 12 $Mg\,ha^{-1}$, depending mainly on the duration of field experiments and soil texture. Annual increase in SOC under NT was 67–512 $kg\,C\,ha^{-1}$ per year. Carbon increase under NT in the Hatton FSL was greater than that in the Swinton SiL. On the Canadian prairies, sandy soils are especially susceptible to wind erosion (Anderson and Wenhardt, 1966) so better crop residue conservation under NT than MT greatly reduces erosion (Saskatchewan Agriculture, 1988). Reduced erosion may have contributed to this greater relative increase in SOC for the Hatton FSL. As mentioned in the methods, severe erosion was noted for MT in 1984 on the Hatton FSL. Wind erosion was not specifically observed in other years or sites but may have occurred.

Only the Indian Head site had a significant crop rotation × tillage interaction for SOC. In contrast to the other rotations, the SOC ranking was MT > NT for PWXwW (Table 6). This was inconsistent with the results for the other sites and for the other rotations at the Indian Head C site. Other studies have found differing effects of tillage for different crop rotations (Potter et al., 1997; Yang and Kay, 2001), although not as dramatic change in effect as we observed for the Indian Head C. Further research is needed to

Table 4
Impact of tillage on BD and SOC in the Hatton fine sandy loam, Swinton silt loam and Sceptre clay

Tillage[a]	Hatton fine sandy loam			Swinton silt loam			Sceptre clay		
	BD	SOC		BD	SOC		BD	SOC	
	$Mg\,m^{-3}$	$mg\,C\,g^{-1}$	$Mg\,C\,ha^{-1}$	$Mg\,m^{-3}$	$mg\,C\,g^{-1}$	$Mg\,C\,ha^{-1}$	$Mg\,m^{-3}$	$mg\,C\,g^{-1}$	$Mg\,C\,ha^{-1}$
	0–7.5 cm								
MT	1.32	9.3	7.9	1.20	15.9	13.1	1.06	15.7	11.7
NT	1.37	10.7	9.3	1.23	17.2	14.1	1.14	17.8	13.3
Contrast "MT versus NT"	<0.01	<0.01	<0.01	NS[b]	<0.01	<0.01	<0.01	0.03	0.03
	7.5–15 cm		0–15 cm	7.5–15 cm		0–15 cm	7.5–15 cm		0–15 cm
MT	1.54	8.5	17.4	1.36	15.6	27.9	1.39	13.6	25.9
NT	1.52	8.5	19.4	1.36	15.2	28.7	1.4	14.4	28.4
Contrast "MT versus NT"	NS	NS	NS	NS	NS	0.02	NS	NS	0.03

[a] CT: cultivator (full) tillage, MT: minimum tillage, NT: no-tillage.
[b] Not significant at $P = 0.10$.

determine the consistency and nature of differences in tillage effects on SOC sequestration for different crop rotations on the Canadian prairies.

It is of interest to note that MT was as effective as NT in sequestering SOC compared with CT in the Indian Head C while the same treatment had no significant impact on SOC in the Melfort SiCL even though these two sites have similar moisture deficits. These contrasting results between the two sites may be explained by frequency of fallow and associated frequency of tillage. At the Melfort site, MT had an rotation average of 1.5 tillage per year with most tillage during fallow. When the soil was moist during fallow, tillage would promote SOC mineralization. At the Indian Head site MT had an rotation average of only one tillage per year.

It is very important to know other possible mechanisms that favor C sequestration under NT in addition to reduced wind erosion in coarse-textured soils. There had been no crop yield differences between tillage systems at the Hatton FSL, Swinton SiL, Sceptre C (McConkey et al., 1996), and at the Melfort SiCL (Zentner et al., 1990). Crop yields averaged 10% higher for NT than CT at the Indian Head C site (Lafond et al., 1992) and 5% higher for NT than CT at the Elstow CL (Brandt, 1992). Therefore, increased production of crop residues cannot explain increased SOC from adoption of NT, although it may be a contributing factor at the Elstow CL and particularly, Indian Head C site.

In order to assess the effect of soil texture on SOC increase the relative annual increase in SOC was calculated as follows:

$$\mathrm{RAISOC} = \frac{\mathrm{SOC_{NT}} - \mathrm{SOC_{CT}}}{\mathrm{SOC_{CT}} \times \mathrm{Years}} \times 100$$

where RAISOC (% per year) is a relative annual increase in SOC per year under NT, $\mathrm{SOC_{NT}}$ the amount of SOC under NT ($Mg\,C\,ha^{-1}$ in the 0–15 cm soil), $\mathrm{SOC_{CT}}$ the amount of SOC under tilled systems ($Mg\,C\,ha^{-1}$ in the 0–15 cm soil), and Year the

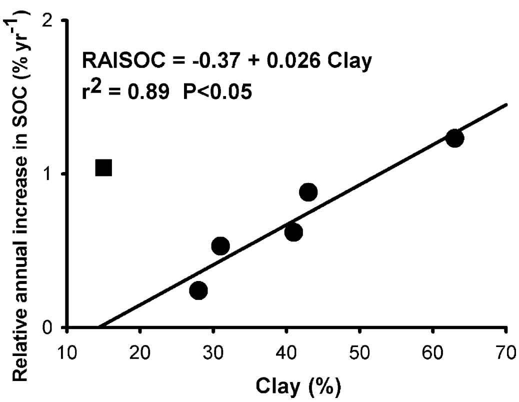

Fig. 1. The relationship between relative annual increase in SOC under NT over tilled systems and clay content of soil (●). The observation for the coarse-textured soil of Hatton fine sandy loam (■) was not used for the regression analysis due to likely impact of wind erosion on tillage effect on SOC.

Table 5
Impact of tillage on BD and SOC in the Elstow clay loam, Melfort silty clay loam, and Indian Head clay

Soil	Tillage[a]	BD	SOC[b]	
		$Mg\,m^{-3}$	$mg\,C\,g^{-1}$	$Mg\,C\,ha^{-1}$
		0–7.5 cm		
Elstow clay loam	CT	1.08	35.2 b	25.1 b
	NT	1.08	39.6 a	28.6 a
		7.5–15 cm		0–15 cm
	CT	1.2	33.3 a	52.2 b
	NT	1.24	33.6 a	56.6 a
		0–7.5 cm		
Melfort silty clay loam	CT	0.94	56.7 b	34.0 b
	MT	0.96	59.3 b	35.6 b
	NT	1.04	67.0 a	40.2 a
		7.5–15 cm		0–15 cm
	CT	1.12	55.1 a	77.2 b
	MT	1.11	63.6 a	84.3 b
	NT	1.25	62.2 a	89.2 a
		0–7.5 cm		
Indian Head clay	CT	1.07	28.7 b	19.6 b
	MT	1.08	33.0 a	22.4 a
	NT	1.1	33.3 a	22.6 a
		7.5–15 cm		0–15 cm
	CT	1.26 ab	23.0 a	39.5 b
	MT	1.22 b	24.1 a	43.6 a
	NT	1.31 a	23.4 a	43.6 a

[a] CT: cultivator (full) tillage, MT: minimum tillage, NT: no-tillage.
[b] Means followed by the same letters within the same column and the same depth of the same soil are not significantly different at $P = 0.05$ probability level.

Table 6
Tillage and crop rotation effects on SOC in the Indian Head clay

Tillage[a]	Crop rotation[b]		
	FWWwW	PWXwW	WWXwW
	0–7.5 cm SOC[c] ($Mg\,ha^{-1}$)		
CT	19.0 c	19.2 bc	19.9 bc
MT	20.1 bc	24.7 a	22.4 ab
NT	22.0 abc	21.4 abc	24.6 a
	0–15 cm SOC[c] ($Mg\,ha^{-1}$)		
CT	38.7 c	39.9 c	39.8 c
MT	40.1 c	47.6 a	43.1 abc
NT	42.5 bc	41.4 c	46.8 ab

[a] CT: cultivator (full) tillage, MT: minimum tillage, NT: no-tillage.
[b] W: spring wheat, F: fallow, X: flax, C: canola, P: pea, wW: winter wheat.
[c] Means followed by the same letter within soil depth are not significantly different at $P = 0.05$ probability level.

number of years since the establishment of tillage experiments.

Relative annual increase in SOC under NT varied from 0.2 to 1.2% per year, mainly depending on the clay content of soil (Fig. 1). If the value of RAISOC for the Hatton FSL were excluded because of probably additional C sequestration associated with reduced wind erosion under NT, there was a linear relationship between RAISOC and the clay content of soil, indicating the role of soil clay content in sequestering C under NT. Because limited number of observations were used for assessing the relationship between the RAISOC and the clay content, we conducted an influential test using SAS (Proc, REG, Option INFLUENCE) (SAS, 1990). We did not find any single observation to have an influential impact on the overall relationship, suggesting that this relationship could be real. We could not separate the influence of texture other site effects so further investigation is warranted to confirm this relationship.

4. Conclusions

The SOC increase for reducing fallow in the sub-humid sites was greater than the semiarid sites. This was despite the fact that continuous cropping represented a smaller decrease in fallow frequency for rotation comparisons in the sub-humid sites than the semiarid sites. Similarly, NT compared with tilled systems increased SOC from 70 to 510 $kg\,C\,ha^{-1}$ per year. The potential for gains in SOC under NT was also greater in the sub-humid soil climates. The relative annual increase in SOC under NT over tilled systems increased approximately linearly with increasing clay content. The combined impact of continuous cropping with adoption of NT resulted in an increase in SOC by approximately 300 $kg\,C\,ha^{-1}$ per year in the semiarid region of the Canadian prairie regardless of soil texture, and approximately

800 kg C ha^{-1} per year in the sub-humid region of the prairie.

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References

Anderson, C.H., Wenhardt, A., 1966. Soil erodibility, fall and spring. Can. J. Soil Sci. 46, 255–299.

Balesdent, J., Chenu, C., Balabane, M., 2000. Relationship of soil organic matter dynamics to physical protection and tillage, Soil Till. Res. 53, 215–230.

Beare, M.H., Caberera, M.L., Hendrix, P.F., Coleman, D.C., 1994. Aggregate-protected and unprotected organic matter pools in conventional- and no-tillage soils. Soil. Sci. Soc. Am. J. 58, 787–795.

Brandt, S.A., 1992. Zero vs. conventional tillage and their effects on crop yield and soil moisture. Can. J. Soil Sci. 72, 679–688.

Campbell, C.A., Zentner, R.P., Janzen, H.H., Bowren, K.E., 1990. Crop rotation studies on the Canadian prairie. Research Branch, Agriculture Canada, Canadian Government Publishing Centre, Supply and Services Canada, Ottawa, Ont., pp. 3–22.

Campbell, C.A., McConkey, B.G., Zentner, R.P., Dyck, F.B., Selles, F., Curtin, D., 1995. Carbon sequestration in a Brown Chernozem as affected by tillage and rotation. Can. J. Soil Sci. 75, 449–458.

Campbell, C.A., McConkey, B.G., Zentner, R.P., Selles, F., Curtin, D., 1996a. Long-term effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. Can. J. Soil Sci. 76, 395–401.

Campbell, C.A., McConkey, B.G., Zentner, R.P., Selles, F., Curtin, D., 1996b. Tillage and crop rotation effects on soil organic C and N in a coarse-textured Typic Haploboroll in southwestern Saskatchewan. Soil Till. Res. 37, 3–14.

Carter, M.R., 1992. Influence of reduced tillage systems on organic matter, microbial biomass, macro-aggregate distribution and structure stability of the surface soil in a humid climate. Soil Till. Res. 23, 361–372.

Doran, J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil. Sci. Soc. Am. J. 44, 765–771.

Dyck, F.B., Tessier, S., 1986. Zero-till drill development at the Swift Current research station, Can. Soc. Agric. Eng. Pap. 86–210. Canadian Society of Agricultural Engineering, Ottawa, Ont.

Ellert, B.H., Bettany, J.R., 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75, 529–538.

Elliott, E.T., Coleman, D.C., 1988. Let the soil work for us. In: Eijsackers, H., Quispel, A. (Eds.), Ecological Implications of Contemporary Agriculture. Proceedings of the 4th European Ecology Symposium, Wageningen, Munksgaard, Copenhagen, pp. 23–32.

Hassink, J., 1994. Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. Soil Biol. Biochem. 26, 1221–1231.

Hassink, J., 1996. Preservation of plant residues in soils differing in unsaturated protective capacity. Soil Sci. Soc. Am. J. 60, 487–491.

Havlin, J.L., Kissel, D.E., Maddux, L.D., Claasen, M.M., Long, J.H., 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54, 448–452.

Janzen, H.H., Campbell, C.A., Izaurralde, R.C., Ellert, B.H., Juma, N., McGill, W.B., Zentner, R.P., 1998. Management effects on soil C storage in the Canadian prairies. Soil Till. Res. 47, 181–195.

Jenkinson, D.S., 1988. Soil organic matter and its dynamics. In: Wild, A. (Ed.), Soil Conditions and Plant Growth, 11th ed. Longman, New York, pp. 564–607.

Ladd, J.N., Amato, M., Odes, J.M., 1985. Decomposition of plant material in Australian soils. III. Residual organic and microbial biomass C and N from isotope-labelled legume material and soil organic matter, decomposing under field conditions. Aust. J. Soil Res. 23, 603–611.

Lafond, G.P., Loeppky, H., Derksen, D.A., 1992. The effects of tillage systems and crop rotations on soil water conservation, seeding establishment and crop yield, seeding establishment and crop yield. Can. J. Plant Sci. 72, 103–115.

Liang, B.C., Gregorich, E.G., MacKenzie, A.F., Schnitner, M., Voroney, R.P., Monreal, C.M., Beyaert, R.P., 1998. Retention and turnover of corn residue carbon. Soil Sci. Soc. Am. J. 62, 1361–1366.

McConkey, B.G., Campbell, C.A., Zentner, R.P., Dyck, F.B., Selles, F., 1996. Long-term tillage effects on spring wheat production on three soil textures in the Brown soil zone. Can. J. Plant Sci. 76, 747–756.

Oades, J.M., 1989. An introduction to organic matter in mineral soils. In: Dixon, J.B., Weed, S.B. (Eds.), Minerals in Soil Environments. Soil Science Society of America, Madison, pp. 89–159.

Potter, K.N., Jones, O.R., Tobert, H.A., Unger, P.W., 1997. Crop rotation and tillage effects on organic carbon sequestration in the semiarid southern Great Plains. Soil Sci. 162, 140–147.

SAS, 1990. SAS User's Guide: Statistics, Version 6. SAS Institute Inc., Cary, NC.

Saskatchewan Agriculture, 1988. Tillage practices that reduce soil erosion. Soil Conservation Notes. ISSN 0829-5751.

Sörensen, L.H., 1981. Carbon–nitrogen relationships during the humification of cellulose in soils containing different amounts of clay. Soil Biol. Biochem. 13, 313–321.

Spain, A., 1990. Influence of environmental conditions and some soil chemical properties on the carbon and nitrogen contents of some tropical Australian rainforest soils. Aust. J. Soil Res. 28, 825–839.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water stable aggregates in soils. J. Soil Sci. 33, 141–163.

Weill, A.N., De Kimpe, C.R., McKyes, E., 1989. Effect of tillage reduction and fertiliser on soil macro- and microaggregates. Can. J. Soil Sci. 68, 489–500.

Yang, X.M., Kay, B.D., 2001. Rotation and tillage effects on soil organic carbon sequestration in a typic Hapludalf in southern Ontario. Soil Till. Res. 59, 107–114.

Zentner, R.P., Bowren, K.E., Edwards, W., Campbell, C.A., 1990. Effects of crop rotations and fertilization on yields and quality of spring wheat grown on a Black Chernozem in north-central Saskatchewan. Can. J. Plant Sci. 70, 387–397.