Soil organic carbon and land use: Processes and potential in Ontario's long-term agro-ecosystem research sites

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¹*School of Environmental Sciences, University of Guelph, Ridgetown Campus, Ridgetown, Ontario, Canada N0P 2C0;* ²*Agriculture and Agri-Food Canada, Guelph, Ontario, Canada N1G 4S9;* ³*Ontario Ministry of Agriculture and Food, Ministry of Rural Affairs, Vineland, Ontario, Canada L0R 2E0;* and ⁴*Department of Plant Agriculture, University of Guelph, Ridgetown Campus, Ridgetown, Ontario, Canada N0P 2C0.*

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Congreves, K. A., Smith, J. M., Németh, D. D., Hooker, D. C. and Van Eerd, L. L. 2014. **Soil organic carbon and land use: Processes and potential in Ontario's long-term agro-ecosystem research sites.** *Can. J. Soil Sci.* **94**: 317–336. Soil organic carbon (SOC) is crucial for maintaining a productive agro-ecosystem. Long-term research must be synthesized to understand the effects of land management on SOC storage and to develop best practices to prevent soil degradation. Therefore, this review compiled an inventory of long-term Ontario studies and assessed SOC storage under common Ontario land management regimes via a meta-analysis and literature review. In general, greater SOC storage occurred in no-till (NT) vs. tillage systems, in crop rotation vs. continuous corn, and in N fertilizer vs. no N fertilizer systems; however, soil texture and perhaps drainage class may determine the effects of tillage. The effect on SOC storage was variable when deeper soil depth ranges (0–45 cm) were considered for NT and rotational cropping, which suggests an unpredictable effect of land management on SOC at depths below the plough layer. Therefore, researchers are encouraged to use the presented inventory of nine long-term research sites and 18 active experiments in Ontario to pursue coordinated studies of long-term land management on SOC at depths extending below the plough layer.

Key words: Meta-analysis, inventory of long-term experiments, soil organic carbon, no-tillage, crop rotation, nitrogen fertilizer

Congreves, K. A., Smith, J. M., Németh, D. D., Hooker, D. C. et Van Eerd, L. L. 2014. **Carbone organique du sol et vocation des terres : mécanismes et possibilités aux sites de recherche de longue haleine sur l'écosystème agricole ontarien.** *Can. J. Soil Sci.* **94**: 317–336. Le carbone organique du sol (COS) est indispensable à la productivité de l'écosystème agricole. Il faut concevoir des études de longue haleine pour bien saisir les conséquences de la vocation des terres sur les réserves de COS et élaborer des pratiques exemplaires qui empêcheront la détérioration du sol. Cet article dresse l'inventaire des études à long terme réalisées en Ontario et évalue le stockage du COS en fonction des régimes de vocation des terres courants dans cette province par la méta-analyse et le dépouillement de la documentation. Dans l'ensemble, il y a plus grande conservation du COS avec le non-travail du sol (NT) qu'avec les systèmes incluant des labours, avec les assolements qu'avec la monoculture du maïs, et avec l'usage d'engrais N que sans fertilisation. Cependant, la texture du sol et éventuellement la classe de drainage pourraient exercer une influence sur les effets du travail du sol. En effet, le stockage du COS varie lorsqu'on tient compte d'une plus grande épaisseur de sol (0–45 cm) dans l'étude du NT et des assolements, ce qui laisse supposer que l'aménagement des terres a un effet imprévisible sur le COS aux profondeurs supérieures à celle de la semelle de labour. En conséquence, les chercheurs sont incités à utiliser l'inventaire des neuf sites de recherche à long terme et des 18 expériences en cours en Ontario présentés dans cet article pour entreprendre des études coordonnées qui feront ressortir les effets de la gestion des terres à long terme sur la COS, à une profondeur supérieure à celle de la semelle de labour.

Mots clés: Méta-analyse, inventaire des expériences de longue haleine, carbone organique du sol, non-travail du sol, assolement, engrais azotés

A recent environmental commissioner's report identified that 44% of Ontario's agricultural cropland was at risk of soil erosion and degradation (Ontario 2009). Soil organic carbon (SOC) is crucial for maintaining long-term resilience of agricultural soils and soil productivity. Thus, land management practices that increase or maintain SOC are needed to prevent soil degradation and to maintain crop

yields and competitiveness of Ontario's agricultural industry. It is therefore essential to understand the effects of land management on SOC in Ontario.

Long-term research provides invaluable insight for quantification of the impact of crop production practices on SOC. The effects of crop production practices on SOC may not be detected with typical timelines of 2–5 yr

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Abbreviations: CT, conventional tillage system; NT, no-till system; SOC, soil organic carbon

in short-term projects. For instance, Smith (2004) reported that soil C inputs increased by 20 to 25%, but it took 6–10 yr for a change in SOC to be detected with a 90% level of confidence. It has been estimated that SOC sequestration rates establish new equilibria in 15–20 yr when comparing no-till (NT) and conventional (CT) practices, and the accumulation of SOC under NT reaches a steady state after 25–30 yr (West and Post 2002; Alvarez 2005). Hence, trials with durations of about 10 yr or more may be most suitable for understanding the dynamics of SOC storage.

International inventories and meta-analyses of long-term soil experiments have been conducted (Powlson et al. 1998; West and Post 2002; Debreczeni et al. 2003). In Canada, a western prairie inventory of long-term soil experiments has been published (Campbell et al. 2012; Lafond and Harker 2012); however, an inventory is lacking for other regions of Canada. Within Ontario, scientists have conducted several long-term field experiments to understand how land management practices such as tillage, crop-rotations, and/or fertilizer affect soil quality parameters such as SOC (Gregorich et al. 1996, 2001; Wanniarachichi et al. 1999; Yang and Kay 2001a, b; VandenBygaart et al. 2002, 2003, 2010; Deen and Kataki 2003; VandenBygaart and Kay 2004; Meyer-Aurich et al. 2006; Angers and Eriksen-Hamel 2008; Yang et al. 2008; Shi et al. 2011; Van Eerd et al. 2014). However, a review of Ontario literature and long-term management practices on SOC is needed to provide relative recommendations on best management practices that maintain or enhance SOC and soil productivity. Therefore, the objectives of this publication were to provide an inventory of long-term research sites in Ontario, assess SOC storage under common Ontario production regimes via a meta-analysis and literature review, and to identify future research needs.

MATERIALS AND METHODS

Results from published long-term research trials, non-peer-reviewed reports and by inquiring at universities and governmental research institutions were amalgamated to review the effect of land use management on SOC in Ontario. The research experiments were long-term trials (>10 yr) that were maintained with consistent treatments as well as recently established trials expected to have a long-term duration. Long-term crop cultivar or watershed experiments were excluded.

Meta-analysis

A dataset was developed from peer-reviewed literature of SOC response to long-term agriculture management in Ontario (Table 1). In order to accurately quantify SOC, the criteria for which literature was used were studies with: >10 yr, SOC on an equivalent basis (Mg C ha^{-1}) by depth, and SOC measured to a depth of at least 30 cm. These criteria were similar to those employed by VandenBygaart and Angers (2006). A previous compendium by VandenBygaart et al. (2003) quantified relative

change of soil C (%) after long-term cropping in Canada, but soil C data were expressed on an area and soil depth basis ranging from 7.5 to 60 cm deep. In the present meta-analysis and for each agriculture management practice evaluated, including tillage, crop rotation, and fertilization, the SOC quantities were assembled for three soil depth ranges: the surface layer (0–10 cm), the plough layer (0–20 cm), and the deeper profile extending below the plough layer (0–30 to 0–45 cm).

A meta-analysis was conducted to accumulate knowledge across studies. From the dataset, specific treatments at depths (0–10, 0–20, 0–45 cm) were paired to determine significant differences in SOC between (a) land use (forest vs. agriculture land); (b) tillage systems (NT or minimal-tillage vs. CT); (c) cropping systems (continuous corn vs. corn in rotation); and (d) N fertilization (N application to corn vs. unfertilized control) (Table 1). Each paired data point was presented as SOC on an area basis, and the change in SOC due to the treatment was calculated as a net change (Mg C ha^{-1}), relative change (%), and rate of change ($\text{g C m}^{-2} \text{ yr}^{-1}$). The distinct subcategories (i.e., soil depth and management practice) permitted comparisons via meta-analysis (Lipsey and Wilson 2000). The change in SOC based on paired treatments was evaluated using the macro developed by Wilson (2005) for an un-weighted meta-analysis in SAS software (SAS Institute, Inc., version 9.3, Cary, NC). The variations associated with the un-weighted means indicated if the treatment effect on SOC was significant (i.e., if the mean $\pm$ standard error overlapped with zero, then the treatment was not significant). Also within each dataset, a PROC MIXED means comparison (LSD test) with the fixed effect of site was applied to test for site variation and significant differences set at $\alpha \leq 0.05$.

RESULTS AND DISCUSSION

Inventory of Ontario Long-term Research Sites

Similar to a Canadian prairie research compilation by Campbell et al. (2012), an inventory of long-term agronomic experiments has been organized and presented herein as a tool for the research community to attain information concerning long-term research sites in Ontario (Table 2). Both published and unpublished research trials have been presented in the inventory (Table 2). The majority of agronomic long-term research in Ontario has focused on field crop rotations involving corn and comparisons of tillage regimes (Table 2), which is representative of the agricultural landscape and management in Ontario. Studies that focused on horticultural production, pasture and livestock grazing systems, organic agriculture and muck soils were not well represented with long-term research in Ontario. As well, some major agricultural production regions in Ontario lack long-term research trials, such as the Niagara region.

To extend Canadian research, data in Table 2 could be merged to the web-based bibliography database Pedosphere.ca - Bibliography of Crop Rotation Studies

Table 1. A compendium of soil organic C (SOC) data derived from Ontario long-term research sites and organized as paired treatments for (i) land use change, and (ii) crop rotation, (iii) tillage system, and (iv) N fertilizer strategies

<i>Land use: forest (control) vs. agricultural (treatment) land</i>									
Site	Control	Treatment ^z	Depth (cm)	Study duration (yr)	SOC control (Mg ha ⁻¹)	SOC TRT (Mg ha ⁻¹)	ΔSOC (Mg ha ⁻¹)	ΔSOC (%)	Reference
Ottawa	Forest	corn, till	30	35 yr - 1945–1979	81.5	98.5	17.1	21.0	Coote and Ramsey (1983)
Ottawa	Forest	corn, till	30	35 yr - 1945–1979	74.9	70.8	-4.1	-5.5	Coote and Ramsey (1983)
Ottawa	Forest	grains, till	30	35 yr - 1945–1979	244.7	207.3	-37.4	-15.3	Coote and Ramsey (1983)
Ottawa	Forest	grains, till	30	35 yr - 1945–1979	64.5	56.6	-8.0	-12.3	Coote and Ramsey (1983)
Winchester	Forest	corn, till	30	25 yr - up to 1991	122.3	96.8	-25.5	-20.9	Gregorich et al. (1996)
Woodslee	Forest	corn, till	40	35 yr - 1959–1994	148.3	92.1	-56.2	-37.9	Gregorich et al. (2001)
Woodslee	Forest	corn, till, no n	40	35 yr - 1959–1994	148.3	81.7	-66.6	-44.9	Gregorich et al. (2001)
Woodslee	Forest	c-o-a-a, till	40	35 yr - 1959–1994	148.3	103.7	-44.6	-30.1	Gregorich et al. (2001)
Woodslee	Forest	c-o-a-a, till, no N	40	35 yr - 1959–1994	148.3	108.8	-39.5	-26.6	Gregorich et al. (2001)
Woodslee	Forest	b, till	40	35 yr - 1959–1994	148.3	122.8	-25.5	-17.2	Gregorich et al. (2001)
Woodslee	Forest	b, till, no N	40	35 yr - 1959–1994	148.3	133.2	-15.1	-10.2	Gregorich et al. (2001)
Elora	Forest	corn, till	30	29 yr - 1967–1995	104.9	60.9	-44.0	-42.0	Wanniarachchi et al. (1999)
Elora	Forest	corn, till	30	29 yr - 1967–1995	104.9	63.6	-41.2	-39.3	Wanniarachchi et al. (1999)
Bond Head	Forest	cereal, forage, bean	31	68 yr - 1927–1995	90.6	68.6	-22.0	-24.3	Ellert and Gregorich (1996)
C. Blondeau	Forest	corn, forage	31	25 yr - 1970–1995	136.7	109.0	-27.7	-20.3	Ellert and Gregorich (1996)
Delhi	Forest	oat, tobacco	31	N/A ^y	55.0	24.6	-30.4	-55.3	Ellert and Gregorich (1996)
Edwards	Forest	corn, cereal, forage	31	N/A	133.6	42.5	-91.1	-68.2	Ellert and Gregorich (1996)
Exeter	Forest	corn, cereal, soybean	31	170 yr - 1825–1995	95.3	59.2	-36.1	-37.9	Ellert and Gregorich (1996)
Fonthill	Forest	forage, cereal, corn	31	195 yr - 1800–1995	79.6	60.9	-18.7	-23.5	Ellert and Gregorich (1996)
Highgate	Forest	corn, soybean	31	N/A	196.6	181.5	-15.1	-7.7	Ellert and Gregorich (1996)
Kapuskasing	Forest	forage, cereal	31	53 yr - 1942–1995	79.4	76.1	-3.3	-4.2	Ellert and Gregorich (1996)
Kemptville	Forest	corn, soybean	31	N/A	81.6	56.7	-24.9	-30.5	Ellert and Gregorich (1996)
Panmure	Forest	forage, cereal, corn	31	145 yr - 1850–1995	84.7	64.7	-20.0	-23.6	Ellert and Gregorich (1996)

Table 1 (Continued)

Land use: forest (control) vs. agricultural (treatment) land										
Site	Control	Treatment ^z	Depth (cm)	Study duration (yr)	SOC control (Mg ha ^{−1})	SOC TRT (Mg ha ^{−1})	ΔSOC (Mg ha ^{−1})	ΔSOC (%)	Reference	
Plainfield	Forest	forage, cereal, corn	31	91 yr - 1904–1995	105.3	62.9	−42.4	−40.3	Ellert and Gregorich (1996)	
Ste. Anne	Forest	forage, corn, cereal	31	85 yr - 1910–1995	108.1	71.1	−37.0	−34.2	Ellert and Gregorich (1996)	
Vineland	Forest	peach, annual ryegrass	31	145 yr - 1850–1995	56.5	40.1	−16.4	−29.0	Ellert and Gregorich (1996)	
Winchester	Forest	corn, forage, soybean	31	105 yr - 1859–1995	127.3	65.3	−62.0	−48.7	Ellert and Gregorich (1996)	
Woodslee	Forest	corn, forage	31	N/A	144.0	76.1	−67.9	−47.2	Ellert and Gregorich (1996)	
Crop rotation: corn (control) vs. legume-based rotation (treatment)										
Site	Control	Treatment	Depth (cm)	Study duration (yr)	SOC Control (Mg ha ^{−1})	SOC TRT (Mg ha ^{−1})	ΔSOC (Mg ha ^{−1})	ΔSOC (%)	ΔSOC (g C m ^{−2} yr ^{−1})	Reference
Elora	cc	a-a-c-c	10	20 yr - 1980–1999	30.0	30.1	0.1	0.2	0.3	Yang and Kay (2001a)
Elora	cc	s-s-c-c	10	20 yr - 1980–1999	30.0	29.4	−0.6	−1.9	−2.8	Yang and Kay (2001a)
Elora	cc	b-rc-c-c	10	20 yr - 1980–1999	30.0	31.4	1.4	4.7	7.0	Yang and Kay (2001a)
Elora	cc	s-w+rc-c-c	10	20 yr - 1980–1999	30.0	29.7	−0.3	−0.8	−1.3	Yang and Kay (2001a)
Elora	cc	s-w-c-c	10	20 yr - 1980–1999	30.0	32.4	2.4	8.0	12.0	Yang and Kay (2001a)
Ridgetown	cc (no till, no N)	c-s (no till, no N)	10	11 yr - 1995–2006	34.8	29.5	−5.3	−15.2	−35.3	unpublished
Ridgetown	cc (no till, no N)	c-s-w (no till, no N)	10	11 yr - 1995–2006	34.8	32.5	−2.3	−6.6	−15.3	unpublished
Ridgetown	cc (till, no N)	c-s (till, no N)	10	11 yr - 1995–2006	23.4	25.8	2.4	10.3	16.0	unpublished
Ridgetown	cc (till, no N)	c-s-w (till, no N)	10	11 yr - 1995–2006	23.4	27.4	4.0	17.1	26.7	unpublished
Ridgetown	cc (no till)	c-s (no till)	10	11 yr - 1995–2006	30.8	30.6	−0.2	−0.6	−1.3	Van Eerd et al. (2014)
Ridgetown	cc (no till)	c-s-w (no till)	10	11 yr - 1995–2006	30.8	35.4	4.6	14.9	30.7	Van Eerd et al. (2014)
Ridgetown	cc (till)	c-s (till)	10	11 yr - 1995–2006	24.7	24.6	−0.1	−0.4	−0.7	Van Eerd et al. (2014)
Ridgetown	cc (till)	c-s-w (till)	10	11 yr - 1995–2006	24.7	27.6	2.9	11.7	19.3	Van Eerd et al. (2014)
Woodslee	cc (till)	c-o-a-a (till)	10	35 yr - 1959–1994	26.9	27.1	0.2	0.7	0.6	Gregorich et al. (2001)
Woodslee	cc (till, no N)	c-o-a-a (till, no N)	10	35 yr - 1959–1994	23.1	27.8	4.7	20.3	13.4	Gregorich et al. (2001)
Elora	cc	a-a-c-c	20	20 yr - 1980–1999	58.7	58.2	−0.6	−1.0	−3.0	Yang and Kay (2001a)
Elora	cc	s-s-c-c	20	20 yr - 1980–1999	58.7	59.4	0.6	1.1	3.1	Yang and Kay (2001a)
Elora	cc	b-rc-b-rc-c-c	20	20 yr - 1980–1999	58.7	61.3	2.6	4.4	12.9	Yang and Kay (2001a)
Elora	cc	s-w+rc-c-c	20	20 yr - 1980–1999	58.7	58.3	−0.4	−0.7	−2.2	Yang and Kay (2001a)
Elora	cc	s-w-c-c	20	20 yr - 1980–1999	58.7	63.5	4.7	8.1	23.7	Yang and Kay (2001a)
Ridgetown	cc (no till, no N)	c-s (no till, no N)	20	11 yr - 1995–2006	63.8	55.1	−8.7	−13.6	−58.0	unpublished
Ridgetown	cc (no till, no N)	c-s-w (no till, no N)	20	11 yr - 1995–2006	63.8	59.3	−4.5	−7.1	−30.0	unpublished
Ridgetown	cc (till, no N)	c-s (till, no N)	20	11 yr - 1995–2006	46.4	52.7	6.3	13.6	42.0	unpublished
Ridgetown	cc (till, no N)	c-s-w (till, no N)	20	11 yr - 1995–2006	46.4	54.7	8.3	17.9	55.3	unpublished
Ridgetown	cc (no till)	c-s (no till)	20	11 yr - 1995–2006	60.2	56.9	−3.3	−5.5	−22.0	Van Eerd et al. (2014)
Ridgetown	cc (no till)	c-s-w (no till)	20	11 yr - 1995–2006	60.2	66	5.8	9.6	38.7	Van Eerd et al. (2014)
Ridgetown	cc (till)	c-s (till)	20	11 yr - 1995–2006	48.8	49.9	1.1	2.3	7.3	Van Eerd et al. (2014)
Ridgetown	cc (till)	c-s-w (till)	20	11 yr - 1995–2006	48.8	53.7	4.9	10.0	32.7	Van Eerd et al. (2014)
Woodslee	cc (till)	c-o-a-a (till)	20	35 yr - 1959–1994	55.6	55.9	0.3	0.5	0.9	Gregorich et al. (2001)
Woodslee	cc (till)	c-o-a-a (till, no N)	20	35 yr - 1959–1994	51.4	56.9	5.5	10.7	15.7	Gregorich et al. (2001)
Elora	cc, no N	b-rc-b-rc-c-c	34	20 yr - 1980–2000	77.7	81.6	3.9	5.0	19.5	Meyer-Aurich et al. (2006)

Table 1 (*Continued*)

<i>Crop rotation: corn (control) vs. legume-based rotation (treatment)</i>										
Site	Control	Treatment	Depth (cm)	Study duration (yr)	SOC Control (Mg ha ⁻¹)	SOC TRT (Mg ha ⁻¹)	ΔSOC (Mg ha ⁻¹)	ΔSOC (%)	ΔSOC (g C m ⁻² yr ⁻¹)	Reference
Elora	cc	s-s-c-c	34	20 yr - 1980–2000	77.7	76.3	−1.4	−1.8	−7.0	Meyer-Aurich et al. (2006)
Elora	cc	s-w-c-c	34	20 yr - 1980–2000	77.7	80.4	2.7	3.5	13.5	Meyer-Aurich et al. (2006)
Elora	cc	s-w + rc-c-c	34	20 yr - 1980–2000	77.7	81.1	3.4	4.4	17.0	Meyer-Aurich et al. (2006)
Elora	cc	a-a-c-c	34	20 yr - 1980–2000	77.7	83.5	5.8	7.5	29.0	Meyer-Aurich et al. (2006)
Elora	cc	a-a-c-c	40	20 yr - 1980–1999	81.2	78.7	−2.5	−3.1	−12.4	Yang and Kay (2001a)
Elora	cc	s-s-c-c	40	20 yr - 1980–1999	81.2	82.0	0.8	0.9	3.8	Yang and Kay (2001a)
Elora	cc	b-rc-b-rc-c-c	40	20 yr - 1980–1999	81.2	85.6	4.3	5.4	21.8	Yang and Kay (2001a)
Elora	cc	s-w + rc-c-c	40	20 yr - 1980–1999	81.2	83.6	2.4	3.0	12.0	Yang and Kay (2001a)
Elora	cc	s-w-c-c	40	20 yr - 1980–1999	81.2	84.6	3.4	4.2	17.1	Yang and Kay (2001a)
Ridgetown	cc (no till, no N)	c-s (no till, no N)	40	11 yr - 1995–2006	107.8	84.7	−23.1	−21.4	−154.0	unpublished
Ridgetown	cc (no till, no N)	c-s-w (no till, no N)	40	11 yr - 1995–2006	107.8	100.5	−7.3	−6.8	−48.7	unpublished
Ridgetown	cc (till, no N)	c-s (till, no N)	40	11 yr - 1995–2006	73.8	81.5	7.7	10.4	51.3	unpublished
Ridgetown	cc (till, no N)	c-s-w (till, no N)	40	11 yr - 1995–2006	73.8	89.3	15.5	21.0	103.3	unpublished
Ridgetown	cc (no till)	c-s (no till)	40	11 yr - 1995–2006	104.2	96.8	−7.4	−7.1	−49.3	Van Eerd et al. (2014)
Ridgetown	cc (no till)	c-s-w (no till)	40	11 yr - 1995–2006	104.2	100.6	−3.6	−3.5	−24.0	Van Eerd et al. (2014)
Ridgetown	cc (till)	c-s (till)	40	11 yr - 1995–2006	79.3	80.9	1.6	2.0	10.7	Van Eerd et al. (2014)
Ridgetown	cc (till)	c-s-w (till)	40	11 yr - 1995–2006	79.3	87.7	8.4	10.6	56.0	Van Eerd et al. (2014)
Woodslee	cc (till)	c-o-a-a (till)	40	35 yr - 1959–1994	92.1	103.7	11.6	12.6	33.1	Gregorich et al. (2001)
Woodslee	cc (till, no till)	c-o-a-a (till, no N)	40	35 yr - 1959–1994	81.7	108.8	27.1	33.2	77.4	Gregorich et al. (2001)
Ridgetown	cc (no till, no N)	c-s (no till, no N)	120	11 yr - 1995–2006	231.3	196	−35.3	−15.3	−235.3	unpublished
Ridgetown	cc (no till, no N)	c-s-w (no till, no N)	120	11 yr - 1995–2006	231.3	212.9	−18.4	−8.0	−122.7	unpublished
Ridgetown	cc (till, no N)	c-s (till, no N)	120	11 yr - 1995–2006	161.7	169.7	8.0	4.9	53.3	unpublished
Ridgetown	cc (till, no N)	c-s-w (till, no N)	120	11 yr - 1995–2006	161.7	186.3	24.6	15.2	164.0	unpublished
Ridgetown	cc (no till)	c-s (no till)	120	11 yr - 1995–2006	221.2	198.3	−22.9	−10.4	−152.7	Van Eerd et al. (2014)
Ridgetown	cc (no till)	c-s-w (no till)	120	11 yr - 1995–2006	221.2	213.4	−7.8	−3.5	−52.0	Van Eerd et al. (2014)
Ridgetown	cc (till)	c-s (till)	120	11 yr - 1995–2006	179	243.7	64.7	36.1	431.3	Van Eerd et al. (2014)
Ridgetown	cc (till)	c-s-w (till)	120	11 yr - 1995–2006	179	170.3	−8.7	−4.9	−58.0	Van Eerd et al. (2014)
<i>Tillage systems: no till (control) vs. tillage (treatment)</i>										
Site	Control	Treatment	Depth (cm)	Study duration (yr)	SOC Control (Mg ha ⁻¹)	SOC TRT (Mg ha ⁻¹)	ΔSOC (Mg ha ⁻¹)	ΔSOC (%)	ΔSOC (g C m ⁻² yr ⁻¹)	Reference
Clinton	no till (c-w)	mb till (c-w)	10	22 yr - 1979–2001	40.1	36.3	−3.8	−9.5	−17.3	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	10	22 yr - 1979–2001	14.6	14.2	−0.4	−2.7	−1.8	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	10	22 yr - 1979–2001	29.5	27.3	−2.2	−7.5	−10.0	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	10	22 yr - 1979–2001	32.6	30.5	−2.1	−6.4	−9.5	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	10	19 yr - 1981–1999	76.2	49.6	−26.6	−34.8	−139.7	Yang and Kay (2001b)
Clinton	no till (c-w)	mb till (c-w)	10	19 yr - 1981–1999	47.7	42.7	−5.0	−10.5	−26.4	Yang and Kay (2001b)

Table 1 (Continued)

Tillage systems: no till (control) vs. tillage (treatment)										
Site	Control	Treatment	Depth (cm)	Study duration (yr)	SOC Control (Mg ha ⁻¹)	SOC TRT (Mg ha ⁻¹)	ΔSOC (Mg ha ⁻¹)	ΔSOC (%)	ΔSOC (g C m ⁻² yr ⁻¹)	Reference
Clinton	no till (c-w)	mb till (c-w)	10	19 yr - 1981–1999	28.7	21.5	-7.2	-25.1	-37.8	Yang and Kay (2001b)
Elora	no till (c-s)	mb till (c-s)	10	25 yr - 1976–2001	22.9	23.6	0.7	2.9	2.7	Deen and Kataki (2003)
Elora	no till (c-s)	mb till (c-s)	10	25 yr - 1976–2001	22.9	18.6	-4.3	-18.8	-17.3	Deen and Kataki (2003)
Elora	no till (c-s)	mb till (c-s)	10	25 yr - 1976–2001	22.9	23.3	0.4	1.8	1.7	Deen and Kataki (2003)
Elora	no till (c-s)	ch till (c-s)	10	25 yr - 1976–2001	22.9	24.4	1.5	6.5	5.9	Deen and Kataki (2003)
Elora	min till (cc)	till (cc)	10	16 yr - 1980–1995	27.3	24.7	-2.6	-9.4	-16.0	Wanniarachchi et al. (1999)
Elora	no till (cc)	mb till (cc)	10	23 yr ^x	30.5	27.5	-3.0	-9.8	-13.0	Yang et al. (2008)
Ridgetown	no till (c-s)	till (c-s)	10	15 yr - 1991–2006	29.2	24.5	-4.7	-16.1	-31.3	Van Eerd et al. (2014)
Ridgetown	no till (cc, no N)	till (cc, no N)	10	11 yr - 1995–2006	34.8	23.4	-11.4	-32.8	-76.0	unpublished
Ridgetown	no till (c-s, no N)	till (c-s, no N)	10	11 yr - 1995–2006	29.5	25.8	-3.7	-12.5	-24.7	unpublished
Ridgetown	no till (c-s-w, no N)	till (c-s-w, no N)	10	11 yr - 1995–2006	32.5	27.4	-5.1	-15.7	-34.0	unpublished
Ridgetown	no till (cc)	till (cc)	10	11 yr - 1995–2006	30.8	24.7	-6.1	-19.8	-40.7	Van Eerd et al. (2014)
Ridgetown	no till (c-s)	till (c-s)	10	11 yr - 1995–2006	30.6	24.6	-6.0	-19.6	-40.0	Van Eerd et al. (2014)
Ridgetown	no till (c-s-w)	till (c-s-w)	10	11 yr - 1995–2006	35.4	27.6	-7.8	-22.0	-52.0	Van Eerd et al. (2014)
Ridgetown	no till (c-s)	ch till (c-s)	10	15 yr - 1991–2006	29.2	26.7	-2.5	-8.6	-16.7	Van Eerd et al. (2014)
Woodslee	no till (w-c-s)	mb till (w-c-s)	10	16 yr - 1993–2009	29.4	25.6	-3.8	-12.9	-23.8	Shi et al. (2011)
Woodslee	no till (c-s)	mb till (c-s)	10	16 yr	38.0	28.0	-10.0	-26.3	-62.5	Yang et al. (2008)
Clinton	no till (c-w)	mb till (c-w)	20	22 yr - 1979–2001	72.7	71.4	-1.3	-1.8	-5.9	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	20	22 yr - 1979–2001	25.7	25.3	-0.4	-1.6	-1.8	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	20	22 yr - 1979–2001	57.1	54.9	-2.2	-3.9	-10.0	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	20	22 yr - 1979–2001	61.7	62.9	1.2	1.9	5.5	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	20	19 yr - 1981–1999	138.1	87.9	-50.2	-36.3	-264.1	Yang and Kay (2001b)
Clinton	no till (c-w)	mb till (c-w)	20	19 yr - 1981–1999	99.5	86.2	-13.3	-13.4	-69.9	Yang and Kay (2001b)
Clinton	no till (c-w)	mb till (c-w)	20	19 yr - 1981–1999	51.5	44.1	-7.5	-14.5	-39.4	Yang and Kay (2001b)
Elora	no till (c-s)	mb till (c-s)	20	25 yr - 1976–2001	43.7	50.4	6.7	15.3	26.8	Deen and Kataki (2003)
Elora	no till (c-s)	mb till (c-s)	20	25 yr - 1976–2001	43.7	42.9	-0.8	-1.8	-3.2	Deen and Kataki (2003)
Elora	no till (c-s)	mb till (c-s)	20	25 yr - 1976–2001	43.7	49.3	5.6	12.8	22.4	Deen and Kataki (2003)
Elora	no till (c-s)	ch till (c-s)	20	25 yr - 1976–2001	43.7	50.0	6.3	14.4	25.2	Deen and Kataki (2003)
Elora	min till (cc)	till (cc)	20	16 yr - 1980–1995	55.7	50.4	-5.2	-9.4	-32.6	Wanniarachchi et al. (1999)
Elora	no till (cc)	mb till (cc)	20	23 yr	58.0	56.1	-1.9	-3.3	-8.3	Yang et al. (2008)
Ridgetown	no till (c-s)	till (c-s)	20	15 yr - 1991–2006	55.4	47.0	-8.4	-15.2	-56.0	Van Eerd et al. (2014)
Ridgetown	no till (cc, no N)	till (cc, no N)	20	11 yr - 1995–2006	63.8	46.4	-17.4	-27.3	-116.0	unpublished
Ridgetown	no till (c-s, no N)	till (c-s, no N)	20	11 yr - 1995–2006	55.1	52.7	-2.4	-4.4	-16.0	unpublished
Ridgetown	no till (c-s-w, no N)	till (c-s-w, no N)	20	11 yr - 1995–2006	59.3	54.7	-4.6	-7.8	-30.7	unpublished
Ridgetown	no till (cc)	till (cc)	20	11 yr - 1995–2006	60.2	48.8	-11.4	-18.9	-76.0	Van Eerd et al. (2014)
Ridgetown	no till (c-s)	till (c-s)	20	11 yr - 1995–2006	56.9	49.9	-7.0	-12.3	-46.7	Van Eerd et al. (2014)
Ridgetown	no till (c-s-w)	till (c-s-w)	20	11 yr - 1995–2006	66.0	53.7	-12.3	-18.6	-82.0	Van Eerd et al. (2014)
Ridgetown	no till (c-s)	ch till (c-s)	20	15 yr - 1991–2006	55.4	48.9	-6.5	-11.7	-43.3	Van Eerd et al. (2014)
Woodslee	no till (w-c-s)	mb till (w-c-s)	20	16 yr - 1993–2009	54.3	51.6	-2.7	-5.0	-16.9	Shi et al. (2011)
Woodslee	no till (c-s)	mb till (c-s)	20	16 yr	64.8	60.7	-4.1	-6.3	-25.6	Yang et al. (2008)

Table 1 (*Continued*)

<i>Tillage systems: no till (control) vs. tillage (treatment)</i>										
Site	Control	Treatment	Depth (cm)	Study duration (yr)	SOC Control (Mg ha ⁻¹)	SOC TRT (Mg ha ⁻¹)	ΔSOC (Mg ha ⁻¹)	ΔSOC (%)	ΔSOC (g C m ⁻² yr ⁻¹)	Reference
Clinton	no till (c-w)	mb till (c-w)	30	22 yr - 1979–2001	80.8	82.4	1.6	2.0	7.3	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	30	22 yr - 1979–2001	32.8	31.0	−1.8	−5.5	−8.2	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	30	22 yr - 1979–2001	78.9	75.2	−3.7	−4.7	−16.8	VandenBygaart and Kay (2004)
Clinton	no till (c-w)	mb till (c-w)	30	22 yr - 1979–2001	93.1	93.9	0.8	0.9	3.6	VandenBygaart and Kay (2004)
Elora	no till	till	30	25 yr - 1980–2005			1.5		6.0	VandenBygaart et al. (2010)
Woodslee	no till (w-c-s)	mb till (w-c-s)	30	16 yr - 1993–2009	72.5	71.7	−0.8	−1.1	−5.0	Shi et al. (2011)
Woodslee	no till	till	30	12 yr - 1996–2005			1.5		12.5	Vandenbygaart et al. (2010)
Clinton	no till (c-w)	mb till (c-w)	40	19 yr - 1981–1999	185.8	110.8	−75.0	−40.4	−394.7	Yang and Kay (2001b)
Clinton	no till (c-w)	mb till (c-w)	40	19 yr - 1981–1999	136.6	125.7	−10.9	−8.0	−57.3	Yang and Kay (2001b)
Clinton	no till (c-w)	mb till (c-w)	40	19 yr - 1981–1999	66.7	65.4	−1.3	−2.0	−7.1	Yang and Kay (2001b)
Elora	no till (c-s)	mb till (c-s)	40	25 yr - 1976–2001	78.2	88.3	10.0	12.8	40.1	Deen and Kataki (2003)
Elora	no till (c-s)	mb till (c-s)	40	25 yr - 1976–2001	78.2	90.0	11.8	15.1	47.3	Deen and Kataki (2003)
Elora	no till (c-s)	mb till (c-s)	40	25 yr - 1976–2001	78.2	85.1	6.9	8.8	27.6	Deen and Kataki (2003)
Elora	no till (c-s)	ch till (c-s)	40	25 yr - 1976–2001	78.2	81.4	3.2	4.1	12.8	Deen and Kataki (2003)
Elora	min till (cc)	till (cc)	40	16 yr - 1980–1995	67.7	67.7	0.0	0.0	0.0	Wanniarachchi et al. (1999)
Elora	no till (cc)	mb till (cc)	40	23 yr	81.6	80.1	−1.5	−1.8	−6.5	Yang et al. (2008)
Ridgetown	no till (c-s)	till (c-s)	40	15 yr - 1991–2006	90.7	73.7	−17.0	−18.7	−113.3	Van Eerd et al. (2014)
Ridgetown	no till (cc, no N)	till (cc, no N)	40	11 yr - 1995–2006	107.8	73.8	−34.0	−31.5	−226.7	unpublished
Ridgetown	no till (c-s, no N)	till (c-s, no N)	40	11 yr - 1995–2006	84.7	81.5	−3.2	−3.8	−21.3	unpublished
Ridgetown	no till (c-s-w, no N)	till (c-s-w, no N)	40	11 yr - 1995–2006	100.5	89.3	−11.2	−11.1	−74.7	unpublished
Ridgetown	no till (cc)	till (cc)	40	11 yr - 1995–2006	104.2	79.3	−24.9	−23.9	−166.0	Van Eerd et al. (2014)
Ridgetown	no till (c-s)	till (c-s)	40	11 yr - 1995–2006	96.8	80.9	−15.9	−16.4	−106.0	Van Eerd et al. (2014)
Ridgetown	no till (c-s-w)	till (c-s-w)	40	11 yr - 1995–2006	100.6	87.7	−12.9	−12.8	−86.0	Van Eerd et al. (2014)
Ridgetown	no till (c-s)	ch till (c-s)	40	15 yr - 1991–2006	90.7	77.6	−13.1	−14.4	−87.3	Van Eerd et al. (2014)
Woodslee	no till (c-s)	mb till (c-s)	40	16 yr	98.9	98.0	−0.9	−0.9	−5.6	Yang et al. (2008)
Dresden	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	56.0	62.1	6.1	10.9	40.7	VandenBygaart et al. (2002, 2003)
Dresden	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	53.3	55.3	2.0	3.8	13.3	VandenBygaart et al. (2002, 2003)
Dresden	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	40.8	35.7	−5.1	−12.5	−34.0	VandenBygaart et al. (2002, 2003)
Dresden	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	36.3	28.0	−8.3	−22.9	−55.3	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	41.1	42.4	1.3	3.2	8.7	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	46.7	59.0	12.3	26.3	82.0	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	37.7	39.2	1.5	4.0	10.0	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	36.0	36.9	0.9	2.5	6.0	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	20.5	16.5	−4.0	−19.5	−26.7	VandenBygaart et al. (2002, 2003)

Table 1 (Continued)

<i>Tillage systems: no till (control) vs. tillage (treatment)</i>										
Site	Control	Treatment	Depth (cm)	Study duration (yr)	SOC Control (Mg ha ⁻¹)	SOC TRT (Mg ha ⁻¹)	ΔSOC (Mg ha ⁻¹)	ΔSOC (%)	ΔSOC (g C m ⁻² yr ⁻¹)	Reference
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	42.4	41.5	−0.9	−2.1	−6.0	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	33.1	35.0	1.9	5.7	12.7	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	30.0	29.8	−0.2	−0.7	−1.3	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	36.4	38.6	2.2	6.0	14.7	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	21.1	8.6	−12.5	−59.2	−83.3	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	49.5	59.0	9.5	19.2	63.3	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	31.3	23.8	−7.5	−24.0	−50.0	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	24.8	21.5	−3.3	−13.3	−22.0	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	33.3	34.1	0.8	2.4	5.3	VandenBygaart et al. (2002, 2003)
Paris	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	45.9	48.4	2.5	5.4	16.7	VandenBygaart et al. (2002, 2003)
Strathroy	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	61.6	81.8	20.2	32.8	134.7	VandenBygaart et al. (2002, 2003)
Strathroy	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	47.7	48.1	0.4	0.8	2.7	VandenBygaart et al. (2002, 2003)
Strathroy	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	43.8	48.4	4.6	10.5	30.7	VandenBygaart et al. (2002, 2003)
Strathroy	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	47.0	56.1	9.1	19.4	60.7	VandenBygaart et al. (2002, 2003)
Strathroy	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	38.9	49.0	10.1	26.0	67.3	VandenBygaart et al. (2002, 2003)
Strathroy	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	46.6	60.9	14.3	30.7	95.3	VandenBygaart et al. (2002, 2003)
Strathroy	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	41.1	38.1	−3.0	−7.3	−20.0	VandenBygaart et al. (2002, 2003)
Strathroy	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	44.1	48.0	3.9	8.8	26.0	VandenBygaart et al. (2002, 2003)
Strathroy	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	44.2	55.1	10.9	24.7	72.7	VandenBygaart et al. (2002, 2003)
Throndale	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	75.1	77.2	2.1	2.8	14.0	VandenBygaart et al. (2002, 2003)
Throndale	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	76.0	88.7	12.7	16.7	84.7	VandenBygaart et al. (2002, 2003)
Throndale	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	48.8	37.2	−11.6	−23.8	−77.3	VandenBygaart et al. (2002, 2003)
Throndale	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	84.1	86.1	2.0	2.4	13.3	VandenBygaart et al. (2002, 2003)
Throndale	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	62.7	66.5	3.8	6.1	25.3	VandenBygaart et al. (2002, 2003)

Table 1 (Continued)

Tillage systems: no till (control) vs. tillage (treatment)										
Site	Control	Treatment	Depth (cm)	Study duration (yr)	SOC Control (Mg ha ⁻¹)	SOC TRT (Mg ha ⁻¹)	ΔSOC (Mg ha ⁻¹)	ΔSOC (%)	ΔSOC (g C m ⁻² yr ⁻¹)	Reference
Throndale	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	39.8	17.8	–22.0	–55.3	–146.7	VandenBygaart et al. (2002, 2003)
Throndale	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	79.1	117.3	38.2	48.3	254.7	VandenBygaart et al. (2002, 2003)
Throndale	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	88.2	108.7	20.5	23.2	136.7	VandenBygaart et al. (2002, 2003)
Throndale	before till (c-s-w)	after mb till	45	15 yr - 1985–2000	47.4	45.5	–1.9	–4.0	–12.7	VandenBygaart et al. (2002, 2003)
Clinton	no till (c-w)	mb till (c-w)	50	19 yr - 1981–1999	198.4	117.8	–80.6	–40.6	–424.3	Yang and Kay (2001b)
Clinton	no till (c-w)	mb till (c-w)	50	19 yr - 1981–1999	151.2	148.6	–2.6	–1.7	–13.6	Yang and Kay (2001b)
Clinton	no till (c-w)	mb till (c-w)	50	19 yr - 1981–1999	84.2	79.9	–4.3	–5.1	–22.6	Yang and Kay (2001b)
Elora	min till (cc)	till (cc)	50	16 yr - 1980–1995	71.7	72.2	0.5	0.7	3.1	Wanniarachchi et al. (1999)
Elora	no till (cc)	mb till (cc)	50	23 yr	87.8	85.3	–2.5	–2.8	–10.9	Yang et al. (2008)
Woodslee	no till (c-s)	mb till (c-s)	50	16 yr	105.9	106.4	0.5	0.5	3.1	Yang et al. (2008)
Elora	no till (c-s)	mb till (c-s)	60	25 yr - 1976–2001	103.7	110.2	6.5	6.2	25.9	Deen and Kataki (2003)
Elora	no till (c-s)	mb till (c-s)	60	25 yr - 1976–2001	103.7	120.9	17.1	16.5	68.6	Deen and Kataki (2003)
Elora	no till (c-s)	mb till (c-s)	60	25 yr - 1976–2001	103.7	99.1	–4.6	–4.4	–18.4	Deen and Kataki (2003)
Elora	no till (c-s)	ch till (c-s)	60	25 yr - 1976–2001	103.7	94.8	–8.9	–8.6	–35.5	Deen and Kataki (2003)
Ridgetown	no till (c-s)	till (c-s)	120	15 yr - 1991–2006	190.9	169.8	–21.1	–11.1	–140.7	Van Eerd et al. (2014)
Ridgetown	no till (cc, no N)	till (cc, no N)	120	11 yr - 1995–2006	231.3	161.7	–69.6	–30.1	–464.0	Van Eerd et al. (2014)
Ridgetown	no till (c-s, no N)	till (c-s, no N)	120	11 yr - 1995–2006	196.0	169.7	–26.3	–13.4	–175.3	Van Eerd et al. (2014)
Ridgetown	no till (c-s-w, no N)	till (c-s-w, no N)	120	11 yr - 1995–2006	212.9	186.3	–26.6	–12.5	–177.3	Van Eerd et al. (2014)
Ridgetown	no till (cc)	till (cc)	120	11 yr - 1995–2006	221.2	179.0	–42.2	–19.1	–281.3	Van Eerd et al. (2014)
Ridgetown	no till (c-s)	till (c-s)	120	11 yr - 1995–2006	198.3	243.7	45.4	22.9	302.7	Van Eerd et al. (2014)
Ridgetown	no till (c-s-w)	till (c-s-w)	120	11 yr - 1995–2006	213.4	170.3	–43.1	–20.2	–287.3	Van Eerd et al. (2014)
Ridgetown	no till (c-s)	ch till (c-s)	120	15 yr - 1991–2006	190.9	178.8	–12.1	–6.3	–80.7	Van Eerd et al. (2014)
Fertilizer Systems: no N fertilizer (control) vs. N fertilizer (treatment)										
Site	Control	Treatment	Depth (cm)	Study duration (yr)	SOC Control (Mg ha ⁻¹)	SOC TRT (Mg ha ⁻¹)	ΔSOC (Mg ha ⁻¹)	ΔSOC (%)	ΔSOC (g C m ⁻² yr ⁻¹)	Reference
Ridgetown	no N (cc, till)	N (cc, till)	10	11 yr - 1995–2006	23.4	30.8	7.4	31.6	49.3	unpublished
Ridgetown	no N (c-s, till)	N (c-s, till)	10	11 yr - 1995–2006	25.8	30.6	4.8	18.6	32.0	unpublished
Ridgetown	no N (c-s-w, till)	N (c-s-w, till)	10	11 yr - 1995–2006	27.4	35.4	8.0	29.2	53.3	unpublished
Woodslee	no N (cc, till)	N (cc, till)	10	32 yr - 1959–1991	19.5	21.8	2.3	11.8	7.2	Gregorich et al. (1996)
Woodslee	no N (cc, till)	N (cc, till)	10	35 yr - 1959–1994	23.1	26.9	3.8	16.5	10.9	Gregorich et al. (2001)
Woodslee	no N (c-o-a-a, till)	N (c-o-a-a, till)	10	35 yr - 1959–1994	27.8	27.1	–0.7	–2.5	–2.0	Gregorich et al. (2001)
Ridgetown	no N (cc, till)	N (cc, till)	20	11 yr - 1995–2006	46.4	60.2	13.8	29.7	92.0	unpublished
Ridgetown	no N (c-s, till)	N (c-s, till)	20	11 yr - 1995–2006	52.7	56.9	4.2	8.0	28.0	unpublished
Ridgetown	no N (c-s-w, till)	N (c-s-w, till)	20	11 yr - 1995–2006	54.7	66.0	11.3	20.7	75.3	unpublished
Woodslee	no N (cc, till)	N (cc, till)	20	32 yr - 1959–1991	39.3	43.5	4.2	10.7	13.1	Gregorich et al. (1996)
Woodslee	no N (cc, till)	N (cc, till)	20	35 yr - 1959–1994	51.4	55.6	4.2	8.2	12.0	Gregorich et al. (2001)
Woodslee	no N (c-o-a-a, till)	N (c-o-a-a, till)	20	35 yr - 1959–1994	56.9	55.9	–1.0	–1.8	–2.9	Gregorich et al. (2001)
Ridgetown	no N (cc, till)	N (cc, till)	40	11 yr - 1995–2006	73.8	104.2	30.4	41.2	202.7	unpublished
Ridgetown	no N (c-s, till)	N (c-s, till)	40	11 yr - 1995–2006	81.5	96.8	15.3	18.8	102.0	unpublished

Table 1 (Continued)

Fertilizer Systems: no N fertilizer (control) vs. N fertilizer (treatment)										
Site	Control	Treatment	Depth (cm)	Study duration (yr)	SOC Control (Mg ha ⁻¹)	SOC TRT (Mg ha ⁻¹)	ΔSOC (Mg ha ⁻¹)	ΔSOC (%)	ΔSOC (g C m ⁻² yr ⁻¹)	Reference
Ridgetown	no N (c-s-w, till)	N (c-s-w, till)	40	11 yr - 1995-2006	89.3	100.6	11.3	12.7	75.3	unpublished
Woodslee	no N (cc, till)	N (cc, till)	40	32 yr - 1959-1991	81.3	89.3	8.0	9.8	25.0	Gregorich et al. (1996)
Woodslee	no N (cc, till)	N (cc, till)	40	32 yr - 1959-1991	46.7	50.0	3.3	7.1	10.3	Gregorich et al. (1996)
Woodslee	no N (cc, till)	N (cc, till)	40	35 yr - 1959-1994	81.7	92.1	10.4	12.7	29.7	Gregorich et al. (2001)
Woodslee	no N (c-o-a-a, till)	N (c-o-a-a, till)	40	35 yr - 1959-1994	108.8	103.7	-5.1	-4.7	-14.6	Gregorich et al. (2001)
Woodslee	no N (cc, till)	N (cc, till)	75	35 yr - 1959-1994	115.5	109.2	-6.3	-5.5	-18.0	Gregorich et al. (2001)
Woodslee	no N (c-o-a-a, till)	N (c-o-a-a, till)	75	35 yr - 1959-1994	129.6	133.8	4.2	3.2	12.0	Gregorich et al. (2001)
Ridgetown	no N (cc, till)	N (cc, till)	120	11 yr - 1995-2006	161.7	221.2	59.5	36.8	396.7	unpublished
Ridgetown	no N (c-s, till)	N (c-s, till)	120	11 yr - 1995-2006	169.7	198.3	28.6	16.9	190.7	unpublished
Ridgetown	no N (c-s-w, till)	N (c-s-w, till)	120	11 yr - 1995-2006	186.3	213.4	27.1	14.5	180.7	unpublished

c, continuous corn; c, corn; s, soybean; w, winter wheat; b, barley; rc, red clover; a, alfalfa; b, bluegrass; till, conventional tillage; mb till, mouldboard plough; ch, chisel plough; no N, no N fertilizer applied; N, N fertilizer applied.

^aN/A, not available.

^bSpecific years not specified.

in the Canadian Prairies available at URL: http://www.pedosphere.ca/CanEduRes/crop_rotations/bibliography.cfm. Opportunities for a more coordinated approach to long-term research could be implemented across Canada, similar to the newly formed USDA Long-term Agro-Ecosystem Research (LTAR) Network for Agriculture (Walbridge and Shafer 2011). Establishing a long-term research network in Ontario may help maintain existing or newly established long-term trials, increase collaboration among researchers, facilitate the use of long-term trials as platforms for testing new hypotheses, and support consistency of data collection among long-term trials. The inclusion of newer (<10 yr) long-term trials in the inventory (Table 2) may stimulate awareness, collaboration, and future research objectives. After all, the success of long-term research depends on collaboration, and the chief justification for its existence is the potential for answering questions not yet envisioned (Janzen 1995).

Long-term Agricultural Land Use

Non-cropped forest soils had $27.6 \pm 3.46\%$ (32.7 ± 4.46 Mg C ha⁻¹) higher SOC than long-term agricultural cropping (Table 3). A previous meta-analysis showed similar reductions of SOC $24 \pm 6\%$ and $22 \pm 9\%$ in long-term cropped soils compared with nearby forested soil across Canada and in eastern Canada, respectively (VandenBygaart et al. 2003). The observed lower SOC in agricultural compared with forest soil may be attributed to reduced C inputs, increased rates of organic matter decay (Ellert and Gregorich 1996) and/or CO₂ efflux. It was previously reported that SOC in cultivated soils in Quebec and Prince Edward Island was lower than the forested area by 35% in Podzolic soils; however, cultivation increased SOC by 25% in Brunisolic and Gleysolic soils (Carter et al. 1998). In Ontario, there was more variability in SOC within forest soil compared with agricultural soil, which was likely due to soil homogenization with tree removal and subsequent land levelling and tillage on agricultural land.

Differences in SOC between adjacent agricultural and forested soil varied across sites, from -3.0% at Ottawa to -68% at Edwards (Table 3). The sites with the greatest difference in SOC (>unweighted mean) between adjacent agricultural and forested soil were Edwards, Elora, Exeter, Plainfield, Ste. Anne, Winchester, and Woodslee (Table 3), of which some common characteristics included soil great groups of mainly the Gray Brown or Luvisol and Humic Gleysol, soil textures of silty loam or silty clay, and the production of corn. Perhaps new site-specific models should be developed to better predict the SOC loss from different soil groups and areas within Ontario. This information may add critical knowledge for soil C processes in differing landscapes, climatic environments, soil types/textures, and management practices in Ontario.

According to the Intergovernmental Panel on Climate Change (IPCC 1997) model: *Soil C managed* = *Soil C*

Table 2. Inventory of long-term agronomic research sites in Ontario

Site	Location	Soil class and texture	Year established	Treatments	Selected representative publications
Woodslee. Agriculture and Agri-Food Canada, Greenhouse and Processing Crops Research Centre. <i>Contact name:</i> Dr. Craig Drury	42°3'N 82°44'W	Orthic Humic Gleysol; clay loam	1959	Rotation: continuous bluegrass, corn-oats-alfalfa-alfalfa, continuous corn; Fertilizer: with and without N fertilizer.	Bolton et al. (1970), Drury and Tan (1995), Drury et al. (2004), Xie et al. (2011), Zhang et al. (2012)
			1983	Tillage: moldboard plough, ridge till, no-till in continuous corn and continuous sod.	Yang et al. (2008), Zhang et al. (2010), Xie et al. (2011); Shi et al. (2011, 2012)
			Since 1997	split-plots with moldboard plough or no-till; added corn- soybean rotation.	
			1993	Tillage: zone tillage, no-tillage and conventional tillage in winter wheat-corn-soybean rotation.	Drury et al. (2012), Sharifi et al. (2008)
Elora. University of Guelph, Elora Research Station. <i>Contact name:</i> Dr. Bill Deen	43°52'N 80°21'W	Gleyed Melanic Brunisol; silt loam	1976	Tillage: no tillage, spring and fall moldboard plough, secondary spring tillage, fall chisel with secondary spring tillage in continuous corn to 1991.	Vyn and Raimbault (1993), Deen and Kataki (2003), Yang et al. (2008)
			Since 1991	in corn-soybean rotation.	
			1980	Rotation: (1) continuous alfalfa, (2) continuous corn, (3) alfalfa-alfalfa-corn-corn, (4) soybean-soybean-corn-corn, (5) barley + red clover-barley + red clover-corn-corn, (6) barley-barley-corn-corn, (7) soybean-winter wheat + red clover-corn-corn, (8) soybean-winter wheat-corn-corn. Tillage: fall moldboard plough, fall chisel plough, spring cultivation- disk.	Wanniarachchi et al. (1999), Yang and Kay (2001a), Mueller et al. (2009a, b), VandenBygaart et al. (2010), Munkholm et al. (2013)
			2008	Fertilizer: N at preplant and sidedress applied at rates of 0, 28, 57, 115, 188 and 230 kg N ha ⁻¹ in corn.	None
Alfred. University of Guelph Alfred Campus. <i>Contact name:</i> Anna Crolla	45°33'N 74°52'W	Gleysol; heavy clay and Brunisol; sandy loam	2005/2006	Fertilizer: raw dairy manure, digestate, inorganic fertilizer on two soil types in continuous silage corn.	Crolla et al. (2013)
Guelph. University of Guelph, Guelph Agroforestry Research Station. <i>Contact name:</i> Drs. Andrew Gordon, Naresh Thevathasan	43°32'N 80°12'W	Gray Brown Luvisol; fine sandy loam	1987	Agroforestry: mixed tree species (predominantly <i>Juglans nigra</i> L. with <i>Quercus rubra</i> L., <i>Fraxinus Americana</i> L. and <i>Robinia pseudoacacia</i> L.)	Thevathasan and Gordon (2004), Peichl et al. (2006), Clinch et al. (2009), Cardinael et al. (2012)
Delhi. (Formerly Agriculture and Agri-Food Canada) Site decommissioned (March 31, 2013). <i>Contact name:</i> Dr. Paul Voroney <i>Contact name:</i> Dr. Bonnie Ball	42°52'N 80°31'W	Brunisol; Gray Brown Luvisol; loamy sand	1988	Rotation: cereal rye-flue cured tobacco-tobacco (established 1933), continuous corn, winter wheat-soybean; Tillage: spring moldboard plough with disk, spring fluted coulter and double disk-seeder; Fertilizer: N rate 0 to 200 kg N ha ⁻¹ .	Murage et al. (2007a, b), Murage and Voroney (2008), Beyaert and Voroney (2011)
	42°47'N 80°38'W	Brunisol; Gray Brown Luvisol; loamy sand	1988	Tillage: no-till, spring mouldboard plough with secondary tillage in continuous corn; Fertilizer: N rate 0 to 200 kg N ha ⁻¹ .	Ball-Coelho and Roy, (1997), Ball-Coelho et al. (1998, 2005), Swanton et al. (1999), Reeleder et al. (2006)
			Since 1993	a rye cover crop in continuous corn.	
Ottawa. Agriculture and Agri-Food Canada, Eastern Cereal and Oilseed Research Centre. <i>Contact name:</i> Dr. Bao-Luo Ma <i>Contact name:</i> Dr. Edward Gregorich	45°23'N 75°43'W	Orthic Humic Gleysol; clay loam	1992	Rotation: corn-soybean, corn-alfalfa continuous corn, Fertilizer: manure, fertilizer.	Ma et al. (1999a, b, 2006, 2012), Gillespie et al. (2014)
		Melanic Brunisol; sandy loam	2000	Rotation: corn-soybean-wheat, continuous corn, continuous soybean, continuous wheat; Tillage: no-till, fall moldboard plough.	Bolinder et al. (1999, 2006), Topp et al. (2000), Carter et al. (2003), Gregorich et al. (2006, 2009), Zhang et al. (2013)
Ridgetown. University of Guelph Ridgetown Campus. <i>Contact name:</i> Dr. David Hooker	42°26'N 81°53'W	Dark Grey Gleysol; clay loam	1995	Rotation: corn-soybean-winter wheat, continuous corn, continuous soybean, corn-soybean, soybean-winter wheat; Tillage: no-till; fall moldboard plough with spring tillage; Fertilizer: with and without N fertilizer.	Van Eerd et al. (2014)

Table 2 (Continued)

Site	Location	Soil class and texture	Year established	Treatments	Selected representative publications
(Site decommissioned spring 2007)	42°27'N 81°53'W	Luvisol; loam	Since 2008	split-plot red clover undersown in winter wheat. Fertilizer: source and placement of P, K; broadcast; starter in corn-soybean-winter wheat	None
	42°26'N 81°53'W	Dark Grey Gleysol; clay loam	1991	Tillage: no-till; fall moldboard plough with spring tillage; fall chisel with spring tillage; ridge-till in soybean-corn rotation.	McGonigle et al. (1999), Van Eerd et al. (2014)
	42°46'N 81°99'W	Luvisol; sandy loam	2007	Cover crops: no cover crop, oat, rye, oilseed radish, mix of rye + oilseed radish in vegetable rotation; Fertilizer: with and without N fertilizer to main crop.	O'Reilly et al. (2011, 2012)
	42°46'N 81°95'W	Luvisol; sandy loam	2008	Cover crops: no cover crop, oat, rye, oilseed radish, vetch, forage pea in vegetable rotation; Cover crop planting date: early Aug; early Sept.	Cartier (2011)
Peterborough. Trent University. <i>Contact name:</i> Dr. Mehdi Sharifi	44°36'N 78°28'W	Melanic Brunisol; loam	2014	Tillage: no-till, moldboard plough with spring tillage: Cover crop: Fertilizer: N rate 0–250 kg N ha ⁻¹ ; P, K in corn-soybean-wheat rotation.	None
	48°22'N 89°22'W	Brunisol; silt clay loam	2004	Rotation: various including alfalfa, barley, soybean, corn, silage corn, winter wheat, ryegrass; Fertilizer: lime, wood ash, solid dairy manure, macro- and micro-nutrient fertilizers.	Thunder Bay Agricultural Research Station Annual Report (2004 to 2013)
Thunder Bay. Thunder Bay Agricultural Research Station <i>Contact name:</i> Dr. Tarlok Singh Sahota			2004	Tillage: fall vs. spring; chisel plough, disk-harrow, cultivation, ridge-till, sub-soil in barley-soybean rotation.	
			2005	Fertilizer: macro and micro nutrients in continuous alfalfa.	

Table 3. Meta-analysis of the effect of forest (control) conversion to long-term cropland (treatment) on the mean change in soil organic C in the 0- to 30-cm or 0- to 40-cm depth at 17 sites in Ontario

Site	Mean change in soil organic C ^z	
	Net (Mg ha ⁻¹) (n = 27)	Relative (%) (n = 28)
Bond Head ^y	-22.0 ^{ab}	-24.3 ^{abcd}
C Blondeau	-27.7 ^{abc}	-20.3 ^{abc}
Delhi	-30.4 ^{abc}	-55.3 ^{cd}
Edwards	-91.1 ^c	-68.2 ^d
Elora	-42.6 ^{abc}	-40.7 ^{bcd}
Exeter	-36.1 ^{abc}	-37.9 ^{abcd}
Fonthill	-18.7 ^{ab}	-23.5 ^{abcd}
Highgate	-15.1 ^{ab}	-7.7 ^{ab}
Kapuskasing	-3.30 ^{ab}	-4.2 ^{ab}
Kemptville	-24.9 ^{ab}	-30.5 ^{abcd}
Ottawa	-8.10 ^a	-3.0 ^a
Panmure	-20.0 ^{ab}	-23.6 ^{abcd}
Plainfield	-42.4 ^{abc}	-40.3 ^{bcd}
Ste. Anne	-37.0 ^{abc}	-34.2 ^{abcd}
Vineland	-16.4 ^{ab}	-29.0 ^{abcd}
Winchester	-43.8 ^{abc}	-34.8 ^{bcd}
Woodslee	-45.1 ^{bc}	-30.6 ^{bc}
Mean	-32.7	-27.6
95% confidence interval	-41.5 to -24.0	-34.4 to -20.8
Standard error	4.46	3.46

^zNegative values indicate lower soil organic C with cropland compared with forest soil.

^yPublications include: Coote and Ramsey (1983), Gregorich et al. (1995), Ellert and Gregorich (1996), Wanniarachchi et al. (1999), Gregorich et al. (2001).

a–d In each column, means followed by different letters indicate a significant difference among sites with a LSD test at $P < 0.05$.

native $\times$ Base factor $\times$ Tillage factor $\times$ Input factors, agricultural production reduces SOC by approximately 30% compared with forested soils, similar to our meta-analysis findings (Table 3). Although there were 17 sites in the meta-analysis, land conversion in northern Ontario was under-represented because only one northern site (Kapuskasing) was included (Fig. 1). Predictions of SOC loss for areas with agricultural potential in northern Ontario would be useful to estimate the future impact of land use transition that may occur with climate change.

Long-term Agricultural Management Practices on SOC

Tillage

The meta-analysis showed long-term NT practices had higher SOC in surface layers (0–10 cm) compared with CT regimes (Table 4), which was consistent with other studies of eastern Canadian soils (Angers et al. 1997; VandenBygaart et al. 2002; Halpern et al. 2010) and elsewhere (Franchini et al. 2007; Fuentes et al. 2009; Deubel et al. 2011). Conventional tillage had 41 g C m⁻² yr⁻¹ less SOC than NT in the shallow soil depth ranges (0–10 cm and 0–20 cm depths) (Table 4), a trend also observed in eastern Canada (Angers et al. 1997; Carter 2005; VandenBygaart et al. 2011) and elsewhere (West

Fig. 1. Soil classification map of southern Ontario with past and present long-term agronomic research sites.

and Post 2002; Luo et al. 2010). The effect of CT vs. NT on SOC in the 0- to 10-cm and 0- to 20-cm depth ranges included only four sites, which included two Gleysols, one Luvisol and one Brunisol, whereas the 0- to 45-cm depth range had a total of eight sites. The four soils that only had data for the 0- to 45-cm depth range had three soils from the Luvisol group and only one soil from the Gleysolic group (Table 4). Thus, the four sites with 0- to 10-cm and 0- to 20-cm data were not representative of the eight sites with 0- to 45-cm data with regards to soil classification or SOC, and a comparison among depth ranges was limited. Readers should not to compare SOC values among these depths (Table 4). Regardless, the greater sample size within the 0- to 45-cm depth ($n=62$) than shallower depth ranges ($n=23$) allowed for greater power for SOC estimates within the 0- to 45-cm depth range.

Overall, most Ontario publications have concluded that NT redistributed SOC within the soil profile but did not increase SOC storage beyond the plough layer (i.e., >20 cm) (Deen and Kataki 2003; Murage et al. 2007a; Angers and Eriksen-Hamel 2008; Yang et al. 2008; Shi et al. 2011). Deen and Kataki (2003) found that NT practices after 25 yr had higher SOC concentrations

compared with CT only for the surface layer at Elora, but not for the 0- to 60-cm depth. No-till practice produced SOC stratification at Woodslee, with greater surface SOC but lower SOC in the 10- to 30-cm layer after 16 yr (Shi et al. 2011). At Delhi, similar SOC depth stratification was observed as NT increased SOC stocks in the 0- to 5-cm depth, but tillage did not alter SOC in the 0- to 20-cm soil depth (Murage et al. 2007a). To detect tillage-induced differences in soil C beyond the plough layer at sites including Woodslee and Elora after 16 and 23 yr, an impractical or expensive amount of minimum core samples may be required (Yang et al. 2008). Other eastern Canadian trials have shown lower SOC in NT than CT at depths below the plough layer (i.e., >20 cm depth) (Angers et al. 1997; VandenBygaart et al. 2003). The accumulation of SOC at the plough layer in CT soils in the cool, humid climates of eastern Canada was suggested to be due to restricted crop residue decomposition after soil inversion with tillage (Angers et al. 1997; Angers and Eriksen-Hamel 2008). Thus, tillage is hypothesized to influence SOC dynamics via the change in soil moisture, temperature, structure, and the mixing of plant residues into soil. However,

Table 4. Meta-analysis of the effect of tillage (treatment) compared to no-tillage (control) on the mean change of soil organic C in three soil depths in Ontario

Site	Soil depth (cm)								
	0–10 (<i>n</i> = 23)			0–20 (<i>n</i> = 23)			0–45 (<i>n</i> = 62)		
	Mean change in soil organic C ^z								
	Net (Mg C ha ^{−1})	Relative (%)	Rate (g C m ^{−2} yr ^{−1})	Net (Mg C ha ^{−1})	Relative (%)	Rate (g C m ^{−2} yr ^{−1})	Net (Mg C ha ^{−1})	Relative (%)	Rate (g C m ^{−2} yr ^{−1})
Clinton ^y	−6.8 <i>a</i>	−14 <i>ab</i>	−34 <i>ab</i>	−11 <i>a</i>	−9.9 <i>b</i>	−55 <i>ab</i>	−13 <i>b</i>	−8.2 <i>bc</i>	−68 <i>bc</i>
Dresden							−1.3 <i>ab</i>	−5.2 <i>abc</i>	−8.8 <i>abc</i>
Elora	−1.2 <i>a</i>	−4.5 <i>a</i>	−6.0 <i>a</i>	1.8 <i>a</i>	4.7 <i>a</i>	5.1 <i>a</i>	4.6 <i>a</i>	6.5 <i>ab</i>	18 <i>a</i>
Paris							0.30 <i>a</i>	−3.0 <i>bc</i> ^x	2.0 <i>ab</i>
Ridgetown	−7.4 <i>a</i>	−22 <i>b</i>	−49 <i>b</i>	−10 <i>a</i>	−16 <i>b</i>	−67 <i>b</i>	−16 <i>b</i>	−15 <i>c</i>	−104 <i>c</i>
Strathroy							7.8 <i>a</i>	16 <i>a</i>	52 <i>a</i>
Thorndale							4.9 <i>a</i>	1.8 <i>abc</i>	32 <i>a</i>
Woodslee	−6.9 <i>a</i>	−20 <i>ab</i>	−43 <i>ab</i>	−3.4 <i>a</i>	−5.7 <i>ab</i>	−21 <i>ab</i>	−4.3 <i>ab</i>	−6.9 <i>abc</i>	−28 <i>abc</i>
Mean	−5.5	−15	−33	−6.5	−8.0	−41	−1.2	−0.83	−6.9
95% Confidence Interval	−8.0 to −3.1	−19 to −10	−47 to −19	−11 to −1.8	−13 to −2.7	−66 to −15	−4.8 to 2.5	−5.7 to 4.1	−29 to 15
Standard error	1.23	2.4	7.1	2.43	2.69	13.2	1.85	2.51	11.17

^zNegative values indicate lower soil organic C with tillage compared with no-till.

^yPublications include: Gregorich et al. (1996), Wanniarachchi et al. (1999) Yang and Kay (2001b), Gregorich et al. (2001), VandenBygaart et al. (2010), Deen and Kataki (2003), VandenBygaart and Kay (2004), Yang et al. (2008), Shi et al. (2011) and Van Eerd et al. (2014).

^xAn outlier was detected within the Paris data for soil organic C relative change (%) based on Lund's test and was not discarded (the presence of the outlier explains the incongruence in sign among integers for the 0–45 cm data at Paris).

a–c In each column, means followed by different letters indicate a significant difference among sites with a LSD test at *P* < 0.05.

interpretations of how tillage affects SOC may differ depending on soil sampling depth range.

For the 0- to 45-cm profile, the presented Ontario meta-analysis showed CT had lower SOC by $6.9 \text{ g C m}^{-2} \text{ yr}^{-1}$ compared with NT (Table 4), but the treatment effect (CT) was not considered significant because the mean $\pm$ standard error (11.17) overlapped with zero. The SOC variability was similar between NT and CT. In contrast with our analysis, a compendium by VandenBygaart et al. (2003) found that eastern Canadian CT soils (pooled depths from 15 to 50 cm profiles) had higher SOC by $7 \text{ g C m}^{-2} \text{ yr}^{-1}$ ($\pm$ standard error of 27) compared with NT soils. The discrepancy may be due to the larger range in soil sample depths by VandenBygaart et al. (2003) of 0–15 to 0–50 cm, compared with 0–30 to 0–45 cm in our study. Within the 0- to 45-cm depth range, four of the soils examined had lower SOC contents when tilled (range of -8.8 to $-104 \text{ g C m}^{-2} \text{ yr}^{-1}$ at Clinton, Dresden, Ridgetown, and Woodslee), whereas four other soils showed that SOC was greater when tilled (range of 2.0 to $52 \text{ g C m}^{-2} \text{ yr}^{-1}$ at Elora, Paris, Strathroy, and Thorndale) (Table 4). Soil texture and possibly drainage class may determine the effects of tillage on SOC. Of the four sites that showed a reduction in 0- to 45-cm SOC due to tillage, three (Dresden, Ridgetown, and Woodslee) were Gleysols (Fig. 1). The four sites that showed a gain in 0- to 45-cm SOC due to tillage (Elora, Paris, Strathroy, and Thorndale) were not Gleysols, but were Brunisols or Luvisols (Fig. 1). Potentially, the long-term disturbance of the soil matrix due to CT vs. NT in Gleysolic soils promoted greater loss of deep SOC (0–45 cm) than in better-drained soils.

Other factors that impact SOC accumulation or loss may have contributed to different rates of SOC change among sites, such as crop biomass, root exudation, and experimental duration. Although the 0- to 45-cm range had a greater sample size than shallower depth ranges (0–10 and 0–20 cm), the effect of tillage on SOC in 0- to 45-cm was more variable than when shallower depth ranges were analyzed, as indicated by site variation, standard errors, and confidence intervals (Table 4). Therefore, the variability of the mean change in SOC analyzed via the mass equivalent basis increased at deeper depth ranges (0–45 cm) relative to shallower depth ranges (0–10, 0–20 cm).

The 0- to 45-cm depth range used in the meta-analysis included data from 0–30 to 0–45 cm but the variability [i.e., standard error of 1.85 for Mg SOC ha^{-1} (Table 4)] did not consistently increase with depth (i.e., the 0- to 30-cm, 0- to 40-cm, and 0- to 45-cm depth ranges had standard errors of 0.94 , 4.7 , 1.7 respectively). Thus, the overall variation in the change in SOC due to CT vs. NT in the 0- to 45-cm depth range was most likely a reflection of the processes of SOC dynamics at deeper profiles. The processes underlying SOC turnover at deeper depths (i.e., >45 cm) are not well known (Schmidt et al. 2011), but our meta-analysis suggests that the stability of SOC at deeper depths was less

predictable than surface SOC. Therefore, researchers should use the sites listed in the inventory (Table 2) to pursue a coordinated study on the effects of long-term tillage management on SOC at deep depths (>45 cm) extending below the tillage layer.

Interestingly, if the Ridgetown site was removed from the current meta-analysis, CT would have had a positive 0- to 45-cm SOC change of $5 \text{ g C m}^{-2} \text{ yr}^{-1}$ ($\pm$ standard error of 11) compared with NT, similar to VandenBygaart et al. (2003). Consequently if one site can alter the results to such an extent, clearly a more comprehensive examination is needed to better understand the effect of tillage on SOC in Ontario. Others have shown soil physical, chemical and climatic indices explained significant amounts of variation in soil N across long-term sites in Canada (Dessureault-Rompré et al. 2010), thus trends in the change of SOC over time may be more consistent within soil type or climate categories in Ontario. The current inventory of long-term sites (Table 2) may be a useful resource for researchers to develop site-specific predictions for SOC change under tillage regimes within Ontario. Previously, a global meta-analysis showed $48 \text{ g C m}^{-2} \text{ yr}^{-1}$ more C sequestered with NT than CT (West and Post 2002). But in the 0- to 40-cm profile, a global meta-analysis of 69 field locations by Luo et al. (2010) found no difference in SOC between long-term NT and CT systems. Although the global reviews inform general predictions (i.e., IPCC models), quantifying the effects of management within smaller regions might be more appropriate for regional policies. Therefore, Ontario policy makers might consider using the presented trends, rather than global reviews, for the effect of CT on SOC storage (Table 4) and for developing best management practices.

Crop Rotation

The meta-analysis showed a positive effect of rotational cropping on SOC compared with continuous corn (Table 5), and agrees with previous meta-analyses, which found that enhancing long-term crop diversity increased SOC accumulation (Drinkwater et al. 1998; West and Post 2002; Eagle and Olander 2012). However, the treatment effect was not considered significant because the means $\pm$ standard error overlapped with zero (Table 5). The effect of rotation on SOC was similar among Elora, Ridgetown, and Woodslee sites at 0- to 10-cm and 0- to 20-cm soil depths (Table 5). However, within the 0- to 45-cm depth there was variation among sites and rotational corn sequestered 22% or 20 Mg C ha^{-1} more SOC than continuous corn at Woodslee compared with Elora or Ridgetown (Table 5). The difference between sites was likely related to the length of the study and the type of rotational crops. The data from Elora and Ridgetown were after 20 and 11 yr, respectively, and included winter wheat, soybean, or winter wheat underseeded with red clover, whereas the Woodslee site had alfalfa rotated with corn for 35 yr. Gregorich et al. (2001) observed at

Soil depth (cm)

²Positive values indicate a higher soil organic C with rotating crops compared to continuous corn.

a-b For each column, means followed by different letters indicate a significant difference among sites with a LSD test at $P < 0.05$.

Other factors associated with rotational cropping compared with continuous corn such as reduced insect and disease pressure can help increase yield and lead to greater residue biomass and soil C input (Drury and Tan 1995). Additionally, the variation in the characteristics and composition of different residue types may contribute to the accumulation of SOC. For example, alfalfa has a deep tap root, which may provide C deeper within the profile where oxygen and microbial activity are typically limited, and therefore contribute to accumulation of SOC (Gregorich et al. 2001). Aromatic C levels were higher below the plough layer in alfalfa rotations, suggesting biological resistance of C degradation (Gregorich et al. 2001). Also, Comeau et al. (2013) found a slower decay rate in pea (*Pisum sativum* L.) compared with other crops, and attributed the difference to recalcitrance of pea root residue deposits and root hairs penetrating stable microaggregates.

Nitrogen Fertilizer

Ridgetown and Woodslee were the only sites included in meta-analysis to investigate the effect of N fertilization on SOC storage in corn rotations (Table 1) because they were the only studies that reported SOC on an equivalent mass basis. The effect of N fertilizer to the corn crop on SOC appeared significant in the 0- to 45-cm depth ($11 \text{ g C m}^{-2} \text{ yr}^{-1}$) but not at shallower layers (-2.1 to $1.5 \text{ g C m}^{-2} \text{ yr}^{-1}$) (Table 6). Nitrogen fertilizer likely facilitated increased SOC sequestration due to increased primary production and thereby greater residue C inputs (Zhang et al. 2012), but research should investigate why the effect on SOC was most pronounced at deeper depths (up to or $>45 \text{ cm}$).

Table 6. Meta-analysis of the effect of N fertilizer (treatment) compared to no N fertilizer (control) on the mean change of soil organic C in three soil depths in Ontario

Site	Soil depth (cm)								
	0–10		0–20				0–45		
	Mean change in soil organic C ^z								
	Net (Mg C ha ⁻¹)	Relative (%)	Rate (g C m ⁻² yr ⁻¹)	Net (Mg C ha ⁻¹)	Relative (%)	Rate (g C m ⁻² yr ⁻¹)	Net (Mg C ha ⁻¹)	Relative (%)	Rate (g C m ⁻² yr ⁻¹)
Ridgetown ^y	-0.4a	-1.2a	-2.4a	-1.7a	-2.9a	-11a	1.3a	2.0a	8.9a
Woodslee	1.8a	8.6a	5.4b	2.5a	5.7a	7.4b	0.15a	1.5a	13a
Mean (<i>n</i> = 6)	0.72	3.7	1.5	0.37	1.4	2.1	2.9	4.4	11
95% Confidence Interval	-0.97 to 2.4	-3.6 to 11	-5.6 to 8.5	-2.8 to 3.5	-5.1 to 7.9	-19 to 15	-1.3 to 7.1	-0.60 to 9.4	-5.4 to 27.4
Standard error	0.860	3.73	3.59	1.622	3.33	8.61	2.14	2.56	8.4

^aPositive values indicate a higher soil organic C with N fertilizer compared with none applied.

^yPublications include: Gregorich et al. (1996, 2001); unpublished for Ridgetown [for site description see Van Eerd et al. (2014)].
a–b For each column, means followed by different letters indicate a significant difference among sites with a LSD test at $P < 0.05$.

Although the corn N fertilization experiment was 12 yr longer at Woodslee than Ridgetown, the meta-analysis showed that the sites had similar positive effect of N fertilization on SOC storage (Table 6). The climatic and soil characteristics were similar between the Ridgetown and Woodslee sites, as the sites are within 100 km of each other, on poorly drained Brookston clay loam soils, and have corn-based cropping sequences. In a global review, Alvarez (2005) concluded that soil C sequestration increased with N application. Although Khan et al. (2007) reported a long-term (51 yr) decline in SOC storage in fertilized continuous corn plots, it is critical to recognize that the choice of baseline can alter the results (Lal 2009). Lal (2009) showed that N fertilizer increased SOC storage based on a treatment comparison between unfertilized and fertilized plots used in the study by Khan et al. (2007). Including other Ontario long-term N fertilization trials could strengthen the conclusions regarding effect on SOC with N fertilizer regimes. Fertilizer trials are presently underway at seven other experiments in Ontario including Ottawa, Alfred, Delhi, Elora, Ridgetown, Peterborough, and Thunder Bay (Table 2). Thus, there is future potential for synthesized Ontario research on N fertilization and SOC.

CONCLUSIONS

Improving the sustainability of Ontario's agriculture depends in part on knowledge gained by long-term cropping practices on SOC. Ontario has a variety of long-term research plots focused on land management and soil productivity; however, research must be synthesized to understand the effects of management on SOC storage and to develop best practices to prevent soil degradation. Our review of long-term agricultural management effects on SOC in Ontario indicated trends towards higher SOC with NT than CT, crop rotation than continuous corn, and N fertilizer than none, similar to previous research. However, SOC loss or gain from tillage practices may be determined by soil classification, texture, and drainage in the 0- to 45-depth range. Management effects on SOC were more variable within deeper profiles (0–45 cm) than within shallower (0–10 and 0–20 cm) profiles. Thus, the stability of deep SOC may be less predictable than shallower depths, and researchers are encouraged to use the inventory of nine Ontario sites and 18 active experimental trials (Table 2) to pursue coordinated studies on the effects of long-term management on SOC at deeper depths (> 45 cm).

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