Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies

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VandenBygaart, A. J., Gregorich, E. G. and Angers, D. A. 2003. **Influence of agricultural management on soil organic carbon: A compendium and assessment of Canadian studies**. Can. J. Soil Sci. **83**: 363–380. To fulfill commitments under the Kyoto Protocol, Canada is required to provide verifiable estimates and uncertainties for **soil organic carbon** (**SOC**) stocks, and for changes in those stocks over time. Estimates and uncertainties for agricultural soils can be derived from long-term studies that have measured differences in SOC between different management practices. We compiled published data from long-term studies in Canada to assess the effect of agricultural management on SOC. A total of 62 studies were compiled, in which the difference in SOC was determined for conversion from native land to cropland, and for different tillage, crop rotation and fertilizer management practices. There was a loss of 24 ± 6% of the SOC after native land was converted to agricultural land. **No-till** (**NT**) increased the storage of SOC in western Canada by 2.9 ± 1.3 Mg ha^{-1}; however, in eastern Canada conversion to NT did not increase SOC. In general, the potential to store SOC when NT was adopted decreased with increasing background levels of SOC. Using no-tillage, reducing summer fallow, including hay in rotation with wheat (*Triticum aestivum* L.), plowing green manures into the soil, and applying N and organic fertilizers were the practices that tended to show the most consistent increases in SOC storage. By relating treatment SOC levels to those in the control treatments, SOC stock change factors and their levels of uncertainty were derived for use in empirical models, such as the United Nations Intergovernmental Panel on Climate Change (IPCC) Guidelines model for C stock changes. However, we must be careful when attempting to extrapolate research plot data to farmers' fields since the history of soil and crop management has a significant influence on existing and future SOC stocks.

Key words: C sequestration, tillage, crop rotations, fertilizer, cropping intensity, Canada

VandenBygaart, A. J., Gregorich, E. G. et Angers, D. A. 2003. **Effet des pratiques agricoles sur le carbone organique dans le sol : compendium et évaluation des études canadiennes**. Can. J. Soil Sci. **83**: 363–380. Pour satisfaire à ses engagements du protocole de Kyoto, le Canada doit soumettre des estimations et des conjectures vérifiables sur les réserves de carbone organique dans ses sols (COS) et leur évolution dans le temps. Pour les sols agricoles, pareilles estimations et conjectures peuvent être dérivées des études de longue haleine mesurant la fluctuation des réserves en fonction de diverses pratiques agricoles. Les auteurs ont colligé les résultats d'études à long terme publiées au Canada afin d'évaluer l'incidence de telles pratiques sur le COS. En tout, 62 études ont été rassemblées et ont servi à établir la variation du COS lorsque les terres passent de l'état naturel à celui de culture, pour divers régimes de travail du sol, d'assolement et d'amendement. Les réserves de COS diminuent de 24 ± 6 % quand on se met à cultiver les terres en friche. Dans l'ouest du pays, le non-travail du sol (NT) accroît les réserves de COS de 2,9 ± 1,3 mg par hectare, mais on n'assiste à aucune hausse de ce genre dans l'Est. En général, le potentiel d'accumulation du COS par le non-travail du sol diminue avec la hausse de la concentration naturelle de COS. Le non-travail du sol, la diminution des jachères estivales, l'intégration du foin et du blé de printemps (*Triticum aestivum* L.) au régime d'assolement, les engrais verts et l'application de N et d'engrais minéraux figurent parmi les pratiques qui tendent à augmenter de la manière la plus soutenue les réserves de COS. Les auteurs sont parvenus à dériver les facteurs de variation des réserves de COS et les niveaux d'incertitude en comparant la concentration de COS résultant de divers traitements à celle des traitements témoins, en vue d'une utilisation dans les modèles empiriques comme celui des lignes directrices du GIEC sur l'évolution des réserves de C. Néanmoins, on doit faire preuve de prudence quand on extrapole les données recueillies sur les parcelles expérimentales aux cultures, car les antécédents pédologiques et agricoles exercent une influence sensible sur les réserves actuelles et futures de COS.

Mots clés: Séquestration du C, travail du sol, assolement, engrais, densité des cultures, Canada

Canada requires verifiable estimates and uncertainties of soil organic carbon (SOC) stocks and changes over time for agricultural soils, to fulfill commitments under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Such estimates can be derived from existing long-term research studies that have documented changes in, or differences between, SOC in various agricultural systems (Janzen et al. 1998). More specifically, we need simple factors that can be used to estimate the existing SOC stock and its change through time for a given system based on existing and future soil management practices. These factors can be used in simple empirical models to assess changes in SOC from field to regional levels (Ellert et al. 2001). The United Nations **Intergovernmental Panel on Climate Change** (**IPCC**) has derived a simple method for calculating SOC stocks in different agricultural land-use and management systems (IPCC 1997) in order to estimate CO_2 emissions from agricultural soils around the world:

$$\text{Soil Carbon}_{\text{managed}} = \text{Soil Carbon}_{\text{native}} \times \text{Base} \times \text{Tillage} \times \text{Input} \quad (1)$$

where Soil $\text{Carbon}_{\text{native}}$ is the carbon content in the native system; the base factor represents changes in SOC content due to conversion of native to agricultural land; the tillage factor and input factors are used to estimate the effect of changes in management practices that occur over the inventory period relative to standard conditions [i.e., conservation tillage vs. conventional tillage; crop rotation vs. monoculture (IPCC 1997)]. However, the IPCC Guidelines for the National Greenhouse Gas Inventories reference manual (IPCC 1997) provides only general base, tillage and input factors that are available for situations where the existing information for a given country is scarce. In Canada, considerable long-term plot research has been focused on determining the effect of soil management practices on SOC. Consequently, there is potential to use data from this research to derive more realistic estimates for the tillage and input factors in the IPCC model, and their levels of uncertainty. This will allow us to make more accurate estimates of existing SOC stocks and the changes that can be expected if management practices are modified. The IPCC Guidelines for the National Greenhouse Gas Inventories method can be used to estimate anthropogenic emissions by sources, and removals by sinks, of greenhouse gases for the calculation of legally binding targets during the first commitment period of the Kyoto Protocol.

The purpose of this paper is: (1) to compile a database on the effects of native-land conversion and management practices on SOC levels in agricultural soils of Canada from long-term studies; (2) to develop factors, and their uncertainties, from the database for use in developing simple empirical models to estimate the existing SOC stock and the changes in SOC stocks due to a change in a management practice in agricultural soils; and (3) to identify information gaps and limitations in estimating agricultural management effects on SOC.

METHODS

Data Compilation and Analysis

We compiled 291 pairs of treatments from long-term field experiments of tillage, rotation and fertilizer inputs, and comparison of native and adjacent agricultural soils, from 62 studies in Canada (Tables 1 and 2). There were at least 3666 soil profiles taken and 4070 treatment years in which SOC was compared between management treatments. Information taken from the studies included SOC content on an area basis (Mg ha^{-1}) from the control and treatment soils, mean annual precipitation and temperature, potential evapotranspiration, soil classification to the Great Group level in the Canadian System of Soil Classification (Agriculture Canada Expert Committee on Soil Survey 1998), textural class, clay content (where available), experiment duration, cropping rotation, fertilizer inputs, tillage treatment, depth of sampling, the number of soil profiles sampled and the type of comparison (i.e., change over time or comparison by treatment). For studies in which agricultural management practices were compared, only those studies in which both bulk density and SOC were determined were reported. For those studies comparing native and cultivated land, and in which organic fertilizers were added, most reported only SOC concentration data; thus relative differences were analyzed. For the treatment duration in each study, we compiled mean annual temperature and precipitation for the meteorological station nearest to the study site (Environment Canada 2002). We also obtained mean annual potential evapotranspiration by summing daily measurements for a given year and averaging over the duration of the treatment period of each study. All data were compiled in a spreadsheet so that analyses could be performed on the entire data set. Data were grouped and assessed based on the type of comparisons being made (i.e., native land conversion, tillage, fertilization, crop rotation) and separate spreadsheets were created for analyses. Data were then grouped based on common characteristics such that the effect of soil, climatic and management factors on changes in SOC with different management treatments could be determined (e.g., effect of tillage on SOC in the different Great Groups; rotation effects on SOC in no-tillage relative to conventional tillage).

Simple regression was used to relate the SOC levels to a control treatment. Since the comparisons of SOC were relative, we forced the trend line through zero, thereby giving a simple multiplicative factor (i.e., if the factor was >1 there was storage of SOC, and if <1 there was a loss of SOC due to the treatment). Since degrees of uncertainty in estimates of SOC storage are critical, we used a conservative estimate of uncertainty and determined 95% confidence intervals for the relationship between SOC in the controls and treatments:

$$x \pm Z\left\{\frac{s}{\sqrt{n}}\right\} \quad (2)$$

where x is the arithmetic mean, s is the standard deviation, Z is the z score at the given level of significance (at 95% confidence $Z = 1.96$), and n is the number of comparisons.

Assumptions

No-till was assumed to have minimal soil disturbance annually, and this disturbance was limited to direct seeding. Depth of soil sampling varied for the studies, but we did not attempt to normalize the data for depth of sampling for SOC. We assumed that the researchers conducting the studies had chosen a sampling depth to adequately determine the management effects on SOC for each study. Of the studies comparing native and cultivated levels of SOC, most were conducted by comparing existing cultivated fields with adjacent native land. In these cases the assumption is implicit

Table 1. Effect of converting native land to agricultural land on SOC

Location (by province from west to east)	MAP[z] (mm)	MAT[z] (°C)	Soil great group[y]/ soil type	Textural class	Relative treatment	Depth of sampling (cm) or horizon	Years since conversion	Δ Soil C (%)	Reference
72 farms in AB	NA[x]	NA	Variable	Variable	Native conversion	NA	Variable	–24%	**Reinl (1984)**
AB, SK and MB	NA	NA	BC	Variable	Grassland conversion	30	Variable	–21%	**Newton et al. (1945)**
AB, SK and MB	NA	NA	DBC	Variable	Grassland conversion	30	Variable	–22%	Newton et al. (1945)
AB, SK and MB	NA	NA	BlC	Variable	Grassland conversion	30	Variable	–18%	Newton et al. (1945)
AB, SK and MB	NA	NA	DGC	Variable	Grassland conversion	30	Variable	–27%	Newton et al. (1945)
SK	NA	NA	BlC	SiL	Grassland conversion	A horizon	60	–32%	**Tiessen et al. (1982)**
SK	NA	NA	BlC	SiL	Grassland conversion	A horizon	90	–58%	Tiessen et al. (1982)
SK	NA	NA	DBC	C	Grassland conversion	A horizon	70	–37%	Tiessen et al. (1982)
SK	NA	NA	DBC	SL	Grassland conversion	A horizon	65	–46%	Tiessen et al. (1982)
central SK	NA	NA	Luvisolic	NA	Forest conversion	45	<=20	–11%	**Pennock and van Kessel (1997)**
central SK	NA	NA	Brunisolic	NA	Forest conversion	45	<=20	–36%	Pennock and van Kessel (1997)
central SK	NA	NA	BlC	SiCL	Grassland conversion	45	>70	–15%	Pennock and van Kessel (1997)
central SK	NA	NA	BlC	CL	Grassland conversion	45	>70	–35%	Pennock and van Kessel (1997)
central SK	NA	NA	BlC	LS	Grassland conversion	45	>70	11%	Pennock and van Kessel (1997)
Matador, SK	NA	NA	BC	C	Grassland conversion	10	20	–19%	**Martel and Paul (1974)**
Quinton, SK	NA	NA	BlC	L	Grassland conversion	10	15	–35%	Martel and Paul (1974)
Quinton, SK	NA	NA	BlC	L	Grassland conversion	12	60	–59%	Martel and Paul (1974)
Hafford, SK	NA	NA	BlC	L	Grassland conversion	10	30	–33%	Martel and Paul (1974)
Swift Current, SK	358	3.5	BC	CL	Grassland conversion	12	14	–27%	**Doughty et al. (1954)**
Swift Current, SK	358	3.5	BC	CL	Grassland conversion	12	14	–24%	Doughty et al. (1954)
Swift Current, SK	358	3.5	BC	C	Grassland conversion	12	12	–17%	Doughty et al. (1954)
Bond Head, ON	1083	5	GBL	SiL	Forest conversion	A horizon	68	–24%	**Ellert and Gregorich (1996)**
C. Blondeau, ON	1176	4.9	HFP	S	Forest conversion	A horizon	25	–20%	Ellert and Gregorich (1996)
Delhi, ON	1009	7.8	GBL	S	Forest conversion	A horizon	NA	–55%	Ellert and Gregorich (1996)
Edwards, ON	915	5.8	MB	SiL	Forest conversion	A horizon	NA	–68%	Ellert and Gregorich (1996)
Exeter, ON	985	7.3	GBL	SiL	Forest conversion	A horizon	170	–38%	Ellert and Gregorich (1996)
Fonthill, ON	936	7.4	GBL	SiCL	Forest conversion	A horizon	195	–23%	Ellert and Gregorich (1996)
Highgate, ON	824	8	HG	SCL	Forest conversion	A horizon	NA	–8%	Ellert and Gregorich (1996)
Kapuskasing, ON	861	0.5	MB	SiCL	Forest conversion	A horizon	53	–4%	Ellert and Gregorich (1996)
Kemptville, ON	996	5.8	MB	SL	Forest conversion	A horizon	NA	–30%	Ellert and Gregorich (1996)
Panmure, ON	776	6	HG	SL	Forest conversion	A horizon	145	–24%	Ellert and Gregorich (1996)
Plainfield, ON	852	7.5	GBL	SiCL	Forest conversion	A horizon	91	–40%	Ellert and Gregorich (1996)
Ste. Anne, ON	836	8.6	MB	SiL	Forest conversion	A horizon	85	–34%	Ellert and Gregorich (1996)
Vineland, ON	836	8.6	GBL	SL	Forest conversion	A horizon	145	–29%	Ellert and Gregorich (1996)
Winchester, ON	996	5.8	HG	SiCL	Forest conversion	A horizon	105	–49%	Ellert and Gregorich (1996)
Woodslee, ON	875	8.7	HG	C	Forest conversion	A horizon	NA	–47%	Ellert and Gregorich (1996)
Ottawa, ON	846	5.9	MB	SL	Forest conversion	30	>35	21%	**Coote and Ramsey (1983)**
Ottawa, ON	846	5.9	MB	LS	Forest conversion	30	>35	–6%	Coote and Ramsey (1983)
Ottawa, ON	846	5.9	HG	C	Forest conversion	30	>35	–15%	Coote and Ramsey (1983)
Ottawa, ON	846	5.9	MB	C	Forest conversion	30	>35	–12%	Coote and Ramsey (1983)
Ste–Anne–de–Bellevue, QC	1020	6	Gleysolic	C	Forest conversion	approx. 25	NA	24%	**Carter et al. (1998)**
Beauce, QC	1008	4	Brunisolic	CL	Forest conversion	approx. 25	NA	31%	Carter et al. (1998)
Lennoxville, QC	1058	5.2	Brunisolic	L	Forest conversion	approx. 25	NA	19%	Carter et al. (1998)
La Pocatiere, QC	967	4.2	Podzolic	SCL	Forest conversion	approx. 25	NA	–54%	Carter et al. (1998)
Isle aux Coudes, QC	NA	NA	HG	CL	Grassland conversion	A and B horizon	NA	–33%	**Martel and Deschenes (1976)**
Charlevoix, QC	NA	NA	HFP	SL	Grassland conversion	A and B horizon	NA	–30%	Martel and Deschenes (1976)
Cantonsde l'Est, QC	NA	NA	HFP	SiL	Grassland conversion	A and B horizon	NA	–36%	Martel and Deschenes (1976)
Harrington, PEI	1077	5.9	Podzolic	FSL	Forest conversion	approx. 25	NA	–11%	**Carter et al. (1998)**
Kelvin Grove, PEI	1000	5.7	Podzolic	FSL	Forest conversion	approx. 25	NA	–29%	Carter et al. (1998)
Mt. Herbert, PEI	1077	5.9	Podzolic	FSL	Forest conversion	approx. 25	NA	–11%	Carter et al. (1998)
Eastern Canada[w]								–22 ± 9%	
Western Canada[w]								–28 ± 7%	
Canada								–24 ± 6%	

[z]MAP = mean annual precipitation, MAT = mean annual temperature.
[y]GBL = Gray-Brown Luvisol, HFP = Humo-Ferric Podzol, MB = Melanic Brunisol, HG = Humic Gleysol, BC = Brown Chernozem, DBC = Dark Brown Chernozem, BlC = Black Chernozem, DGC = Dark Gray Chernozem.
[x]Not applicable or not available.
[w]Ontario-Manitoba border as boundary between eastern and western Canada.

Table 2. Differences in SOC as a result of agricultural management practices

Location (by province from west to east)	MAP (mm)	MAT (°C)	PET	Soil great group[z]	Textural class	Duration (yr)	Treatment[x]	Depth sampled (cm)	Soil profiles sampled	SOC control (Mg ha^{-1})	Net C difference (Mg ha^{-1})	C storage rate (g C m^{-2} yr^{-1})	Reference
Summerland, BC	290	9.0	711	BC	LS	4	organic fertilizer	15	8	44.6	3.1	78.7	**Zebarth et al. (1999)**
Summerland, BC	290	9.0	711	BC	LS	3	organic fertilizer	15	8	44.6	15.5	515.3	Zebarth et al. (1999)
Summerland, BC	290	9.0	711	BC	LS	4	organic fertilizer	15	8	44.6	54.8	1369.3	Zebarth et al. (1999)
Lethbridge, AB	402	5.0	732	BC	CL	41	cont. w vs. f-w	30	20	58.3	2.1	5	**Bremer et al. (1994)**
Lethbridge, AB	402	5.0	732	BC	CL	41	cont. w vs. f-w	30	20	57.9	3.0	7	Bremer et al. (1994)
Lethbridge, AB	402	5.0	732	BC	CL	41	organic fertilizer	30	20	57.8	4.9	12	Bremer et al. (1994)
Lethbridge, AB	402	5.0	732	BC	CL	41	hay in rotation	30	20	57.8	6.4	16	Bremer et al. (1994)
Bow Island, AB	370	5.0	732	BC	CL	6	f-w-w vs. f-w	30	16	20.2	0.7	12	Bremer et al. (2002)
Bow Island, AB	370	5.0	732	BC	CL	6	cont. w vs. f-w	30	16	20.2	1.5	25	Bremer et al. (2002)
Bow Island, AB	370	5.0	732	BC	CL	6	crested w-grass vs. f-w-w	30	16	20.9	2.3	38	Bremer et al. (2002)
Bow Island, AB	370	5.0	732	BC	CL	6	crested w-grass vs. f-w	30	16	20.2	3.0	50	Bremer et al. (2002)
Lethbridge, AB	402	5.0	758	DBC	L	9	straw	20	12	42.7	0.2	3	**Dormaar and Carefoot (1998)**
Lethbridge, AB	402	5.0	758	DBC	L	9	NT variable rotation	20	12	42.7	8.2	91	Dormaar and Carefoot (1998)
Lethbridge, AB	402	5.0	758	DBC	L	9	inorganic fertilizer	20	12	41.5	2.3	25	Dormaar and Carefoot (1998)
Lethbridge, AB	402	5.0	758	DBC	L	9	inorganic fertilizer	20	12	20.8	3.0	33	Dormaar and Carefoot (1998)
Lethbridge, AB	402	5.0	736	DBC	L	10	organic fertilizer	20	5	38.0	12.0	120	Dormaar and Sommerfeld (1986)
Lethbridge, AB	402	5.0	736	DBC	L	10	organic fertilizer	20	5	38.0	30.0	300	Dormaar and Sommerfeld (1986)
Beaverlodge, AB	468	2.0	568	GL	CL	7	NT variable rotation	20	32	140.4	15.4	221	**Franzluebbers and Arshad (1996)**
Lethbridge, AB	402	5.0	777	DBC	CL	4	NT w-sugar beet-legume	30	128	28.3	1.8	45	**Hao et al. (2001)**
Lethbridge, AB	402	5.0	736	BC	CL	16	NT f-w	15	30	27.1	2.1	13	**Larney et al. (1997)**
Lethbridge, AB	402	5.0	736	BC	CL	16	NT f-w	15	30	27.6	1.6	10	Larney et al. (1997)
Lethbridge, AB	402	5.0	736	BC	CL	16	NT f-w	15	30	30.4	–1.2	–8	Larney et al. (1997)
Lethbridge, AB	402	5.0	754	BC	CL	8	NT cont. w	15	25	31.0	2.0	25	Larney et al. (1997)
Lethbridge, AB	402	5.0	754	BC	CL	9	cont. w vs. f-w (CT)	15	30	38.5	2.8	31	Larney et al. (1997)
Lethbridge, AB	402	5.0	739	DBC	CL	24	NT f-w	20	12	37.1	–3.2	–13	**Miller et al. (1999)**
Crossfield, AB	450	2.3	646	BlC	NA[w]	27	inorganic fertilizer	30	60	112.9	18.5	68	Malhi et al. (1997)
Crossfield, AB	450	2.3	646	BlC	NA	27	inorganic fertilizer	30	60	112.9	23.4	87	Malhi et al. (1997)
Crossfield, AB	450	2.3	646	BlC	NA	27	inorganic fertilizer	30	60	112.9	24.6	91	Malhi et al. (1997)
Crossfield, AB	450	2.3	646	BlC	NA	27	inorganic fertilizer	30	60	112.9	18.4	68	Malhi et al. (1997)
Crossfield, AB	450	2.3	641	BlC	L	23	inorganic fertilizer	15	60	71.8	4.0	17	Malhi et al. (2002)
Crossfield, AB	450	2.3	641	BlC	L	23	inorganic fertilizer	15	60	71.8	3.4	15	Malhi et al. (2002)
Breton, AB	547	2.1	580	GL	L	42	inorganic fertilizer	Apu	2[t]	20.3[u]	0.8	2	**Izaurralde et al. (2001)**
Breton, AB	547	2.1	580	GL	L	42	organic fertilizer	Apu	2[t]	20.3[u]	7.5	18	Izaurralde et al. (2001)
Breton, AB	547	2.1	580	GL	L	42	inorganic fertilizer	Apu	5[t]	32.4[u]	4.7	11	Izaurralde et al. (2001)
Breton, AB	547	2.1	580	GL	L	49	inorganic fertilizer	Apu	4[t]	20.3[u]	–0.8	–2	Izaurralde et al. (2001)
Breton, AB	547	2.1	580	GL	L	49	organic fertilizer	Apu	4[t]	20.3[u]	9.5	19	Izaurralde et al. (2001)
Breton, AB	547	2.1	580	GL	L	49	inorganic fertilizer	Apu	20[t]	34.7[u]	4.7	10	Izaurralde et al. (2001)
Breton, AB	547	2.1	580	GL	L	60	inorganic fertilizer	Apu	2[t]	16.6[u]	1.2	2	Izaurralde et al. (2001)
Breton, AB	547	2.1	580	GL	L	60	organic fertilizer	Apu	2[t]	16.6[u]	15.2	25	Izaurralde et al. (2001)
Breton, AB	547	2.1	580	GL	L	60	inorganic fertilizer	Apu	10[t]	34.7[u]	4.7	8	Izaurralde et al. (2001)
Breton, AB	547	2.1	580	GL	L	18	f-w from time 0	Apu	2[t]	21.1[u]	–3.2	–18	Izaurralde et al. (2001)
Breton, AB	547	2.1	580	GL	L	11	NT cont. barley	15	40	32.1	5.9	53.4	**Nyborg et al. (1995)**
Breton, AB	547	2.1	580	GL	L	11	NT cont. barley	15	40	34.5	7.5	68.2	Nyborg et al. (1995)
Breton, AB	547	2.1	580	GL	L	11	NT cont. barley	15	40	30.3	1.8	16.5	Nyborg et al. (1995)
Breton, AB	547	2.1	580	GL	L	11	straw	15	40	30.5	1.6	14.1	Nyborg et al. (1995)
Breton, AB	547	2.1	580	GL	L	11	straw	15	40	28.7	1.5	14.0	Nyborg et al. (1995)
Breton, AB	547	2.1	580	GL	L	11	NT cont. barley	15	40	30.3	0.3	2.5	Nyborg et al. (1995)
Ellersie, AB	455	1.9	560	BlC	L	11	NT cont. barley	15	40	88.3	1.8	15.9	Nyborg et al. (1995)
Ellersie, AB	455	1.9	560	BlC	L	11	NT cont. barley	15	40	87.8	1.9	17.1	Nyborg et al. (1995)
Ellersie, AB	455	1.9	560	BlC	L	11	NT cont. barley	15	40	83.6	0.8	7.4	Nyborg et al. (1995)
Ellersie, AB	455	1.9	560	BlC	L	11	straw	15	40	83.6	4.2	38.4	Nyborg et al. (1995)
Breton, AB	547	2.1	570	GL	L	12	inorganic fertilizer	15	32	34.9	2.0	16.7	**Solberg et al. (1997)**
Breton, AB	547	2.1	570	GL	L	12	inorganic fertilizer	15	32	34.9	7.7	64.2	Solberg et al. (1997)
Breton, AB	547	2.1	570	GL	L	12	inorganic fertilizer	15	32	34.9	8.1	67.5	Solberg et al. (1997)
Breton, AB	547	2.1	570	GL	L	12	straw	15	32	36.8	–2.8	–23.3	Solberg et al. (1997)
Ellersie, AB	455	1.9	580	BlC	L	12	inorganic fertilizer	15	32	146.0	3.0	25.2	Solberg et al. (1997)
Ellersie, AB	455	1.9	580	BlC	L	12	inorganic fertilizer	15	32	146.0	4.0	33.7	Solberg et al. (1997)
Ellersie, AB	455	1.9	580	BlC	L	12	inorganic fertilizer	15	32	146.0	7.2	59.7	Solberg et al. (1997)
Ellersie, AB	455	1.9	580	BlC	L	12	straw	15	32	146.2	–0.2	–1.7	Solberg et al. (1997)
Ellersie, AB	455	1.9	580	BlC	L	12	straw	15	32	146.2	–0.2	–1.7	Solberg et al. (1997)
Ellersie, AB	455	1.9	580	BlC	L	12	straw	15	32	146.6	2.5	20.7	Solberg et al. (1997)
Ellersie, AB	455	1.9	580	BlC	L	12	straw	15	32	148.8	1.2	10.2	Solberg et al. (1997)
Ellersie, AB	455	1.9	580	BlC	L	12	straw	15	32	153.0	0.2	1.3	Solberg et al. (1997)
Breton, AB	547	2.1	570	GL	L	12	straw	15	32	36.8	–1.9	–15.8	Solberg et al. (1997)
Breton, AB	547	2.1	570	GL	L	12	straw	15	32	33.5	3.4	28.3	Solberg et al. (1997)

Table 2. Continued

Breton, AB	547	2.1	570	GL	L	12	straw	15	32	38.4	4.2	35.0	Solberg et al. (1997)
Breton, AB	547	2.1	570	GL	L	12	straw	15	32	42.7	0.3	2.5	Solberg et al. (1997)
Breton, AB	547	2.1	633	GL	SiL	63	legumes in rotation	15	6	17.0	10.0	16	**Grant et al. (2001)**
Breton, AB	547	2.1	633	GL	SiL	63	organic fertilizer	15	6	19.0	13.0	21	Grant et al. (2001)
Swift Current, SK	358	3.5	684	BC	SiL	16	f-w-w vs. f-w	15	9	32.8	–0.7	–5	**Biederbeck et al. (1984)**
Swift Current, SK	358	3.5	684	BC	SiL	16	f-w-w vs. f-w	15	9	32.2	–2.7	–17	Biederbeck et al. (1984)
Swift Current, SK	358	3.5	684	BC	SiL	16	flax in rotation	15	9	32.0	–0.4	–2	Biederbeck et al. (1984)
Swift Current, SK	358	3.5	684	BC	SiL	16	rye in rotation	15	9	34.8	–1.5	–9	Biederbeck et al. (1984)
Swift Current, SK	358	3.5	684	BC	SiL	16	f-w-w vs. f-w	15	9	30.9	0.7	5	Biederbeck et al. (1984)
Swift Current, SK	358	3.5	684	BC	SiL	16	oats in rotation	15	9	34.4	–0.2	–1	Biederbeck et al. (1984)
Swift Current, SK	358	3.5	684	BC	SiL	16	flax in rotation	15	9	38.1	–2.2	–14	Biederbeck et al. (1984)
Swift Current, SK	358	3.5	684	BC	SiL	16	cont. w vs. f-w	15	9	37.3	0.5	3	Biederbeck et al. (1984)
Swift Current, SK	358	3.5	684	BC	SiL	16	inorganic fertilizer	15	9	32.2	1.1	7	Biederbeck et al. (1984)
Swift Current, SK	358	3.5	693	BC	SiL	6	gm in rotation	10	16	20.4	1.1	18	Biederbeck et al. (1998)
Swift Current, SK	358	3.5	693	BC	SiL	6	cont. w vs. f-w	10	16	20.4	1.2	21	Biederbeck et al. (1998)
Swift Current, SK	358	3.5	683	BC	SL	18	f-w-w vs. f-w	15	6	30.9	0.5	3	**Campbell and Zentner (1993)**
Swift Current, SK	358	3.5	683	BC	SL	18	flax in rotation	15	6	31.4	–2.8	–16	Campbell and Zentner (1993)
Swift Current, SK	358	3.5	683	BC	SL	18	rye in rotation	15	6	31.4	1.6	9	Campbell and Zentner (1993)
Swift Current, SK	358	3.5	683	BC	SL	18	inorganic fertilizer	15	6	31.4	2.9	16	Campbell and Zentner (1993)
Swift Current, SK	358	3.5	683	BC	SL	18	legumes in rotation	15	6	34.3	0.9	5	Campbell and Zentner (1993)
Swift Current, SK	358	3.5	683	BC	SL	18	cont. w vs. f-w	15	6	30.9	3.4	19	Campbell and Zentner (1993)
Swift Current, SK	358	3.5	683	BC	SL	18	cont. w vs. f-w-w	15	6	31.4	2.9	16	Campbell and Zentner (1993)
Swift Current, SK	358	3.5	683	BC	SL	18	inorganic fertilizer	15	6	30.2	1.2	7	Campbell and Zentner (1993)
Swift Current, SK	358	3.5	671	BC	SiL	12	NT cont. w	7.5	18	14.6	1.3	11	**Campbell et al. (1995a)**
Swift Current, SK	358	3.5	671	BC	SiL	12	NT f-w	7.5	18	13.9	0.9	8	Campbell et al. (1995a)
Swift Current, SK	358	3.5	671	BC	SiL	12	cont. w vs. f-w	7.5	18	14.8	1.1	9	Campbell et al. (1995a)
Stewart Valley, SK	409	4.3	684	BC	CL	11	NT f-w	15	18	24.3	5.2	47	**Campbell et al. (1996a)**
Stewart Valley, SK	409	4.3	684	BC	CL	11	NT cont. w	15	18	25.8	2.7	25	Campbell et al. (1996a)
Stewart Valley, SK	409	4.3	684	BC	CL	11	cont. w vs. f-w	15	18	29.4	–0.9	–8	Campbell et al. (1996a)
Swift Current, SK	358	3.5	671	BC	SL	11	NT f-w	15	18	19.6	0.0	0	**Campbell et al. (1996b)**
Swift Current, SK	358	3.5	671	BC	SL	11	NT cont. w	15	18	18.0	1.0	9	Campbell et al. (1996b)
Swift Current, SK	358	3.5	671	BC	SL	11	cont. w vs. f-w	15	18	19.0	0.6	6	Campbell et al. (1996b)
Indian Head, SK	427	2.5	675	BlC	HC	39	inorganic fertilizer	15	8	30.4	2.0	5	**Campbell et al. (1998)**
Indian Head, SK	427	2.5	675	BlC	HC	39	f-w-w vs. f-w	15	8	32.4	3.8	10	Campbell et al. (1998)
Indian Head, SK	427	2.5	675	BlC	HC	39	gm in rotation	15	8	33.9	0.0	0	Campbell et al. (1998)
Indian Head, SK	427	2.5	675	BlC	HC	39	inorganic fertilizer	15	8	34.3	1.9	5	Campbell et al. (1998)
Indian Head, SK	427	2.5	675	BlC	HC	39	hay in rotation	15	8	35.6	2.3	6	Campbell et al. (1998)
Indian Head, SK	427	2.5	675	BlC	HC	39	cont. w vs. f-w	15	8	32.4	7.3	19	Campbell et al. (1998)
Indian Head, SK	427	2.5	675	BlC	HC	39	inorganic fertilizer	15	8	32.6	7.1	18	Campbell et al. (1998)
Indian Head, SK	427	2.5	675	BlC	HC	39	cont. w vs. f-w-w	15	8	32.4	7.3	19	Campbell et al. (1998)
Swift Current, SK	358	3.5	676	BC	SL	29	inorganic fertilizer	15	6	30.0	3.4	12	**Campbell et al. (2000a)**
Swift Current, SK	358	3.5	676	BC	SL	29	f-w-w vs. f-w	15	6	30.0	2.8	10	Campbell et al. (2000a)
Swift Current, SK	358	3.5	676	BC	SL	29	rye in rotation	15	6	30.0	6.9	24	Campbell et al. (2000a)
Swift Current, SK	358	3.5	676	BC	L	10	f-w-w from time 0	30	6	29.5	3.9	39	**Campbell et al. (2000b)**
Swift Current, SK	358	3.5	676	BC	L	10	f-w-w from time 0	30	6	29.9	1.9	19	Campbell et al. (2000b)
Swift Current, SK	358	3.5	676	BC	L	10	f-w-w from time 0	30	6	31.0	2.2	22	Campbell et al. (2000b)
Swift Current, SK	358	3.5	676	BC	L	10	gm in rotation	30	6	27.8	4.4	44	Campbell et al. (2000b)
Swift Current, SK	358	3.5	676	BC	L	10	f-w-w-w from time 0	30	6	27.3	5.8	58	Campbell et al. (2000b)
Swift Current, SK	358	3.5	676	BC	L	10	cont. w from time 0	30	6	29.2	6.0	60	Campbell et al. (2000b)
Swift Current, SK	358	3.5	676	BC	L	10	crested w-grass from time 0	30	6	29.4	1.7	17	Campbell et al. (2000b)
Indian Head, SK	427	2.5	675	BlC	NA	10	NT f-w	15	8	28.8	2.6	26	**Campbell et al. (2001a)**
Indian Head, SK	427	2.5	675	BlC	NA	10	NT f-w	15	8	29.1	3.9	39	Campbell et al. (2001a)
Indian Head, SK	427	2.5	675	BlC	NA	10	NT f-w-w	15	8	29.8	–1.8	–18	Campbell et al. (2001a)
Indian Head, SK	427	2.5	675	BlC	NA	10	NT f-w-w	15	8	29.9	5.2	52	Campbell et al. (2001a)
Indian Head, SK	427	2.5	675	BlC	NA	10	NT f-w-w	15	8	28.6	4.9	49	Campbell et al. (2001a)
Indian Head, SK	427	2.5	675	BlC	NA	10	NT gm	15	8	32.5	–1.3	–13	Campbell et al. (2001a)
Indian Head, SK	427	2.5	675	BlC	NA	10	NT f-w-w-hay	15	8	33.6	0.9	9	Campbell et al. (2001a)
Indian Head, SK	427	2.5	675	BlC	NA	10	NT cont. w	15	8	30.8	0.0	0	Campbell et al. (2001a)
Indian Head, SK	427	2.5	675	BlC	NA	10	NT cont. w	15	8	34.5	2.0	20	Campbell et al. (2001a)
Swift Current, SK	358	3.5	676	BC	L	32	f-w-w vs. f-w	15	32	54.3	4.8	15	**Campbell et al. (2001b)**
Swift Current, SK	358	3.5	676	BC	L	32	f-w-w-w-w-w vs. f-w	15	32	54.3	4.8	15	Campbell et al. (2001b)
Swift Current, SK	358	3.5	676	BC	L	32	f-w-w vs. f-w-w-w-w-w	15	32	59.1	0.0	0	Campbell et al. (2001b)
Indian Head, SK	427	2.5	657	BlC	NA	29	inorganic fertilizer	15	12	36.3	1.6	6	**Campbell et al. (1991a)**
Indian Head, SK	427	2.5	657	BlC	NA	29	f-w-w vs. f-w	15	12	36.3	0.1	0	Campbell et al. (1991a)
Indian Head, SK	427	2.5	657	BlC	NA	29	f-w-w vs. f-w	15	12	37.9	0.6	2	Campbell et al. (1991a)
Indian Head, SK	427	2.5	657	BlC	NA	29	gm in rotation	15	12	36.4	3.1	11	Campbell et al. (1991a)
Indian Head, SK	427	2.5	657	BlC	NA	29	gm in rotation	15	12	36.4	3.5	12	Campbell et al. (1991a)
Indian Head, SK	427	2.5	657	BlC	NA	29	hay in rotation	15	12	36.4	5.8	20	Campbell et al. (1991a)
Indian Head, SK	427	2.5	657	BlC	NA	29	hay in rotation	15	12	36.4	5.1	18	Campbell et al. (1991a)
Indian Head, SK	427	2.5	657	BlC	NA	29	cont. w vs. f-w	15	12	36.3	3.3	11	Campbell et al. (1991a)
Indian Head, SK	427	2.5	657	BlC	NA	29	cont. w vs. f-w	15	12	37.9	4.0	14	Campbell et al. (1991a)
Indian Head, SK	427	2.5	657	BlC	NA	30	inorganic fertilizer	15	12	36.4	2.1	7	Campbell et al. (1991a)
Indian Head, SK	427	2.5	657	BlC	NA	30	straw	15	12	38.5	–0.3	–1	Campbell et al. (1991a)

Table 2. Continued

Melfort, SK	506	0.8	588	BlC	NA	31	f-w-w vs. f-w	15	12	62.4	–1.2	–4	**Campbell et al. (1991b)**
Melfort, SK	506	0.8	588	BlC	NA	31	gm in rotation	15	12	62.4	–0.4	–1	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	gm in rotation	15	12	62.4	3.7	12	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	cont. w vs. f-w-w	15	12	61.4	3.9	13	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	cont. w vs. f-w	15	12	62.4	3.0	10	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	inorganic fertilizer	15	12	65.3	0.1	0	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	hay in rotation	15	12	61.4	4.1	13	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	hay in rotation	15	12	61.4	5.2	17	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	hay in rotation	15	12	61.4	2.3	7	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	hay in rotation	15	12	61.2	4.7	15	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	hay in rotation	15	12	61.2	2.3	7	Campbell et al. (1991b)
Melfort, SK	506	0.8	588	BlC	NA	31	hay in rotation	15	12	61.2	0.1	0	Campbell et al. (1991b)
Scott, SK	350	0.8		DBC	L	24	f-can-w vs. f-can	7.5	12	35.5	–2.6	–11	**Campbell et al. (1992)**
Scott, SK	350	0.8		DBC	L	24	cont w. vs. f-can	7.5	12	35.5	–1.8	–8	Campbell et al. (1992)
Scott, SK	350	0.8		DBC	L	24	cont w. vs. f-can-w	7.5	12	32.9	0.8	3	Campbell et al. (1992)
Swift Current, SK	358	3.5	676	BC	L	10	crested w-grass vs. f-w-w	15	6	29.2	1.8	18	**Curtin et al. (2000a)**
Swift Current, SK	358	3.5	676	BC	L	10	crested w-grass vs. f-w-w	15	6	33.7	–2.7	–27	Curtin et al. (2000a)
Swift Current, SK	358	3.5	676	BC	L	10	crested w-grass vs. f-w-w	15	6	33.1	–2.1	–21	Curtin et al. (2000)
Swift Current, SK	358	3.5	678	BC	SL	8	crested w-grass	15	6	32.0	–1.0	–13	Curtin et al. (2000a)
Swift Current, SK	358	3.5	678	BC	SL	8	gm in rotation	15	6	30.6	0.5	6	**Curtin et al. (2000b)**
Indian Head, SK	427	2.5	681	BlC	HC	4	NT variable rotation	15	4	46.8	3.7	93	**Grant and Lafond (1994)**
Indian Head, SK	427	2.5	681	BlC	HC	4	NT variable rotation	15	4	46.8	3.9	98	Grant and Lafond (1994)
Melfort, SK	411	0.3	588	BlC	SiCL	25	NT f-w	15	12	77.2	12.0	48	**McConkey et al. (2003)**
Elstow, SK	355	1	625	BlC	CL	16	NT variable rotation	15	12	52.2	4.4	28	McConkey et al. (2003)
Indian Head, SK	427	2	577	BlC	C	8	NT variable rotation	15	12	39.5	4.1	51	McConkey et al. (2003)
Canwood, SK	456	0.3	624	DGC	L	12	inorganic fertilizer	30	80	89.2	3.9	32.3	**Nyborg et al. (1999)**
Canwood, SK	456	0.3	620	BlC	SL-SCL	12	inorganic fertilizer	37.5	28	114.0	–10.0	–83.3	**Nyborg et al. (1998)**
Canwood, SK	456	0.3	620	BlC	SL-SCL	12	inorganic fertilizer	37.5	28	114.0	0.0	0.0	Nyborg et al. (1998)
Canwood, SK	456	0.3	620	BlC	SL-SCL	12	inorganic fertilizer	37.5	28	114.0	6.0	50.0	Nyborg et al. (1998)
Canwood, SK	456	0.3	620	BlC	SL-SCL	12	inorganic fertilizer	37.5	28	114.0	–11.0	–91.7	Nyborg et al. (1998)
Melfort, SK	506	0.8	557	BC	SiCL	3	inorganic fertilizer	15	40	NA	NA	NA	**Pare et al. (1999)**[y]
Melfort, SK	506	0.8	557	BC	SiCL	3	organic fertilizer	15	40	NA	NA	NA	Pare et al. (1999)
Melfort, SK	506	0.8	557	BC	SiCL	3	organic fertilizer	15	40	NA	NA	NA	Pare et al. (1999)
Ottawa, ON	846	5.9	633	MB	SL	5	NT cont. c	60	16	74.8	6.0	120	**Angers et al. (1997)**
Ottawa, ON	846	5.9	633	MB	SL	5	NT cont. w	60	16	65.9	14.8	297	Angers et al. (1997)
Delhi, ON	935	7.8	720	GBL	SL	4	NT cont. c	60	16	30.0	–3.1	–77	Angers et al. (1997)
Harrow, ON	819	8.7	673	LG	CL	11	NT cont. c	60	16	82.7	–0.9	–8	Angers et al. (1997)
Woodlsee, ON	875	8.7	720	HG	CL	32	inorganic fertilizer	42	4	81.3	8.0	25	**Gregorich et al. (1996)**
Woodlsee, ON	875	8.7	720	HG	CL	35	legumes in rotation vs. cont. c	70	3	115.5	14.1	40	**Gregorich et al. (2001)**
Woodlsee, ON	875	8.7	720	HG	CL	35	legumes in rotation vs. cont. c	70	3	109.2	24.6	70	Gregorich et al. (2001)
Thorndale, ON	800	7.9	686	GBL	SiL	15	NT c-w-s	45	1	75.1	–2.1	–13.7	**VandenBygaart et al. (2002)**
Thorndale, ON	800	7.9	686	GBL	SiL	15	NT c-w-s	45	1	76.0	–12.7	–85.0	VandenBygaart et al. (2002)
Thorndale, ON	800	7.9	686	GBL	SiL	15	NT c-w-s	45	1	48.8	11.6	77.4	VandenBygaart et al. (2002)
Thorndale, ON	800	7.9	686	GBL	SiL	15	NT c-w-s	45	1	84.1	–2.0	–13.4	VandenBygaart et al. (2002)
Thorndale, ON	800	7.9	686	GBL	SiL	15	NT c-w-s	45	1	62.7	–3.8	–25.5	VandenBygaart et al. (2002)
Thorndale, ON	800	7.9	686	GBL	SiL	15	NT c-w-s	45	1	39.8	22.0	146.5	VandenBygaart et al. (2002)
Thorndale, ON	800	7.9	686	GBL	SiL	15	NT c-w-s	45	1	79.1	–38.2	–254.9	VandenBygaart et al. (2002)
Thorndale, ON	800	7.9	686	GBL	SiL	15	NT c-w-s	45	1	88.2	–20.5	–136.4	VandenBygaart et al. (2002)
Thorndale, ON	800	7.9	686	GBL	SiL	15	NT c-w-s	45	1	47.4	1.9	13.0	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	41.1	–1.3	–8.6	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	46.7	–12.3	–82.1	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	37.7	–1.5	–10.0	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	36.0	–0.9	–5.8	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	20.5	4.0	26.6	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	42.4	0.9	5.9	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	33.1	–1.9	–12.6	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	30.0	0.2	1.5	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	36.4	–2.2	–14.7	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	21.1	12.5	83.3	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	49.5	–9.5	–63.4	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	31.3	7.5	50.2	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	24.8	3.3	21.8	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	33.3	–0.8	–5.5	VandenBygaart et al. (2002)
Paris, ON	855	7.9	657	GBL	SL	15	NT c-w-s	45	1	45.9	–2.5	–16.9	VandenBygaart et al. (2002)
Dresden, ON	817	8.3	725	GBL	CL	15	NT c-w-s	45	1	56.0	–6.1	–41.0	VandenBygaart et al. (2002)
Dresden, ON	817	8.3	725	GBL	CL	15	NT c-w-s	45	1	53.3	–2.0	–13.4	VandenBygaart et al. (2002)
Dresden, ON	817	8.3	725	GBL	CL	15	NT c-w-s	45	1	40.8	5.1	34.0	VandenBygaart et al. (2002)
Dresden, ON	817	8.3	725	GBL	CL	15	NT c-w-s	45	1	36.3	8.3	55.2	VandenBygaart et al. (2002)
Strathroy, ON	958	7.9	681	GBL	SL	15	NT c-w-s	45	1	61.6	–20.2	–134.4	VandenBygaart et al. (2002)
Strathroy, ON	958	7.9	681	GBL	SL	15	NT c-w-s	45	1	47.7	–0.4	–2.7	VandenBygaart et al. (2002)
Strathroy, ON	958	7.9	681	GBL	SL	15	NT c-w-s	45	1	43.8	–4.6	–30.5	VandenBygaart et al. (2002)
Strathroy, ON	958	7.9	681	GBL	SL	15	NT c-w-s	45	1	47.0	–9.1	–60.6	VandenBygaart et al. (2002)

Table 2. Continued

Strathroy, ON	958	7.9	681	GBL	SL	15	NT c-w-s	45	1	38.9	–10.1	–67.5	VandenBygaart et al. (2002)
Strathroy, ON	958	7.9	681	GBL	SL	15	NT c-w-s	45	1	46.6	–14.3	–95.3	VandenBygaart et al. (2002)
Strathroy, ON	958	7.9	681	GBL	SL	15	NT c-w-s	45	1	41.1	3.0	19.7	VandenBygaart et al. (2002)
Strathroy, ON	958	7.9	681	GBL	SL	15	NT c-w-s	45	1	44.1	–3.9	–26.2	VandenBygaart et al. (2002)
Strathroy, ON	958	7.9	681	GBL	SL	15	NT c-w-s	45	1	44.2	–10.9	–72.9	VandenBygaart et al. (2002)
Delhi, ON	935	7.8	710	GBL	LS	6	NT cont. c	50	20	23.4	–1.3	–21.0	**Wanniarachchi et al. (1999)**
Elora, ON	939	6.3	610	MB	SiL	29	NT cont. c	50	20	72.2	–0.5	–1.7	Wanniarachchi et al. (1999)
Elora, ON	939	6.3	637	MB	SiL	19	NT cont. c	15	4	21.9	0.2	0.8	**Winter et al. (1990)**
Elora, ON	939	6.3	628	MB	SiL	20	NT c-w-s	40	20	81.9	6.8	34.0	**Yang and Kay (2001a)**
Elora, ON	939	6.3	628	MB	SiL	20	legumes in rotation vs. cont. c	40	20	81.2	4.3	21.8	Yang and Kay (2001a)
Clinton, ON	943	7.3	642	GBL	SL	19	NT c-w-s	30	4	105.1	70.1	369.2	**Yang and Kay (2001b)**
Clinton, ON	943	7.3	642	GBL	LS	19	NT c-w-s	30	6	112.9	14.7	77.4	Yang and Kay, (2001b)
Clinton, ON	943	7.3	642	GBL	CL	19	NT c-w-s	30	8	61.9	–4.7	–24.7	Yang and Kay, (2001b)
St-Lambert, QC	1200	4	653	OG	SiL	11	NT cont. c	24	12	91.3	2.7	25	**Angers et al. (1993)**
St-Lambert, QC	1200	4	653	OG	SiL	11	NT cont. c	24	12	65.9	17.3	157	**Angers et al. (1995)**
St-Lambert, QC	1200	4	653	OG	SiL	11	NT cont. c	24	12	64.9	3.8	35	Angers et al. (1995)
La Pocatiere, QC	967	4.2	552	HG	C	6	NT cont. barley	60	16	91.0	–20.3	–338	**Angers et al. (1997)**
Normandin, QC	866	0.9	584	HG	CL	4	NT cont. barley	60	16	71.7	–6.5	–162	Angers et al. (1997)
Normandin, QC	866	0.9	584	HG	SiC	3	NT cont. barley	60	16	111.9	–5.5	–182	Angers et al. (1997)
Normandin, QC	866	0.9	584	HG	SiC	3	NT cont. barley	60	16	111.9	2.7	90	Angers et al. (1997)
Ste-Anne-de-Bellevue, QC			557	DB	SCL	6	inorganic fertilizer	20	NA	40.7	2.4	40	**Liang and Mackenzie (1992)**
Fourchette, QC				HG	SL	9	organic fertilizer	15	NA	NA	NA	NA	**N'dayegamire and Angers (1993)**[y]
Fourchette, QC				HG	SL	9	organic fertilizer	15	NA	NA	NA	NA	N'dayegamire and Angers (1993)
Fourchette, QC				HG	SL	9	organic fertilizer	15	NA	NA	NA	NA	N'dayegamire and Angers (1993)
Fourchette, QC				HG	SL	9	inorganic fertilizer	15	NA	NA	NA	NA	N'dayegamire and Angers (1993)
Harrington, PEI	1077	5.9	487	HFP	FSL	8	NT w-barley-s	60	16	92.9	–8.0	–99	**Angers et al. (1997)**
Charlottetown, PEI	1077	5.9	487	GBL	L	8	NT w-barley-s	60	16	44.8	–0.7	–9	Angers et al. (1997)
Charlottetown, PEI	1077	5.9	487	HFP	SL	3	NT cont. potato	30	20	70.7	–4.2	–141	**Carter and Kunelius (1986)**
Harrington, PEI	1200	5.2	487	HFP	FSL	5	NT barley-potato	8	18	16.6	0.5	9	**Carter and Sanderson (2001)**
Harrington, PEI	1200	5.2	487	HFP	FSL	5	NT barley-forage-potato	8	18	16.7	1.7	34	Carter and Sanderson (2001)
Charlottetown, PEI	1077	5.9	487	HFP	NA	6	NT cont. c	16	4	15.2	1.9	32	**Carter et al. (2002)**
PEI	1077	5.9	487	GL	L	8	NT variable	40	20	47.4	–5.9	–74	**Carter (1996)**

[z]OG = Orthic Gleysol, GBL = Gray-Brown Luvisol, HFP = Humo-Ferric Podzol, MB = Melanic Brunisol, HG = Humic Gleysol, BC = Brown Chernozem, DBC = Dark Brown Chernozem, BlC = Black Chernozem, DGC = Dark Gray Chernozem, GL = Gray Luvisol, OG = Orthic Gleysol, LG = Luvic Gleysol.
[y]SOC in concentration only.
[x]NT relative to CT, c = corn, cont. c = continuous corn, can. = canola, w = wheat, b = barley, h = hay, cont. w = continuous wheat, f-w = fallow-wheat rotation, f-w-w = fallow-wheat-wheat rotation, gm = green manure, c-w-s = corn-wheat-soybean in rotation; treatments "in rotation", organic fertilizer, inorganic fertilizer and straw are relative to an unamended control.
[w]NA, not available in publication or not applicable.
[v]Canola assumed to have similar carbon inputs relative to wheat (C. Campbell, personal communication, Agriculture and Agri-Food Canada, Ottawa, ON).
[u]Samples taken in Ap horizon and Ap thickness and bulk density from one sample period used in calculation of SOC on an area basis.
[t]Minimum since number of samples varied between plots.

that the baseline or starting point for SOC was the same at both locations in the landscape. Furthermore, all but three of the studies comparing SOC in native and cultivated land made comparisons on a concentration basis, and differences in bulk density were not accounted for. In five of the seven sites compared by Carter et al. (1998), and 11 of 15 sites compared by Ellert and Gregorich (1996), the bulk density was lower in the forested sites relative to adjacent cultivated soils, suggesting there can be varying effects of plowing cultivated soils on soil bulk density, which will further influence SOC stock measurements.

Only two of the agricultural management studies were side-by-side comparisons on transects; most studies were conducted in block designs in which the comparison of SOC was taken as a difference due to treatment. It was assumed that this difference represented the change in SOC in a farmer's field that occurred as a result of a similar treatment over the period that the study was conducted. Only three studies involved measuring SOC levels at the beginning and end of the experiment to determine the net change. In all cases the assumption was made that the SOC was at steady state at the start of the experiment and that any changes in SOC were due to the treatments imposed thereafter within the time period. We determined the rates of change of SOC for the given treatments by dividing the difference in SOC by the number of years since the treatment was imposed. We recognize that such changes in SOC are usually nonlinear and often approach an asymptote. However, due to the nature of most of the experimental designs, we assumed the rates of change in SOC to be linear and acknowledge that the rates would likely decrease with time as SOC approached a new steady state (Janzen et al. 1998).

Table 3. Effect of NT on SOC in Great Groups of the Canadian System of Soil Classification (1998), for Eastern and Western Canada and for all of Canada

Great group[z]	Net difference (Mg ha^{-1})	Relative difference (%)	Storage rate (g C m^{-2} yr^{-1})	Regression coefficient[y]	Mean duration (yr)	Comparisons (*n*)	Soil profiles (*n*)	References[w]
BC	1.6 ± 1.0	6.9 ± 3.9	13 ± 9	1.07 ± 0.05*	12.3 ± 2.3	11	223	1-4
BlC	3.5 ± 1.6	8.6 ± 3.8	37 ± 16	1.06 ± 0.03***	10.6 ± 2.4	17	236	5-8
DBC	5.3 ± 3.7	14.6 ± 7.0	63 ± 24	1.16 ± 0.04*	8.0 ± 3.5	4	144	9-11
GL	2.8 ± 4.1	7.6 ± 10.0	28 ± 49	1.07 ± 0.13	9.8 ± 1.5	6	212	5,12,13
GBL	–2.7 ± 3.6	–0.2 ± 9.8	–20 ± 24	0.90 ± 0.07**	14.4 ± 0.8	38	108	14-16
HFP	–1.6 ± 3.8	2.2 ± 8.2	–33 ± 71	0.93 ± 0.05*	5.4 ± 1.6	5	76	17-20
HG	–3.0 ± 6.2	–1.7 ± 9.8	–70 ± 101	0.95 ± 0.09	9.5 ± 4.1	10	64	16,19
LG	-0.9	–1.1	–9	NA	11	1	16	19
OG	3.8	3.8	35	NA	11	1	76	21
MB	5.5 ± 5.4	7.8 ± 8.1	90 ± 110	1.09 ± 0.11†	15.6 ± 9.1	5	36	19,22,23
Western Canada	2.9 ± 1.3	7.3 ± 2.6	32 ± 15	1.07 ± 0.02***	11.4 ± 1.5	35	795	1-12
Eastern Canada	–0.1 ± 3.4	–0.1 ± 5.0	–7 ± 27	0.96 ± 0.04†	12.9 ± 1.2	63	396	13-23
Canada	0.4 ± 1.5	3.7 /- 4.0	5 ± 16	0.99 ± 0.03	12.3 ± 1.0	98	1191	1-23

[z]GBL = Gray-Brown Luvisol, HFP = Humo-Ferric Podzol, MB = Melanic Brunisol, HG = Humic Gleysol, BC = Brown Chernozem, DBC = Dark Brown Chernozem, BlC = Black Chernozem, DGC = Dark Gray Chernozem, GL = Gray Luvisol, OG = Orthic Gleysol, LG = Luvic Gleysol.

[y]Derived by linear regression as the slope between SOC in management treatment versus the SOC in the control treatment and forced through zero.

[x]Campbell et al. (1996a) (1), Campbell et al. (1996b) (2), Campbell et al. (1995a) (3), Larney et al. (1997) (4), Nyborg, et al. (1995) (5), Campbell et al. (2001a) (6), Grant and Lafond (1994) (7), McConkey et al. (2003) (8), Hao et al. (2001) (9), Elliott and Efetha (1999) (10), Doormar and Carefoot (1998) (11), Franzluebbers and Arshad (1996) (12), Carter (1996) (13), Yang and Kay, (2001a) (14), Wanniarachchi et al., (1999) (15), VandenBygaart et al. (2002) (16), Carter et al. (2002) (17), Carter and Sanderson 2001 (18), Angers, et al. (1997) (19), Carter and Kunelius 1986 (20), Angers et al. 1995 (21), Winter et al. 1990 (22), Yang and Kay (2001b) (23).

†,*,**,*** denote coefficient significantly different than 1 at $P < 0.10$, $P < 0.05$, $P < 0.01$, $P < 0.001$ respectively.

RESULTS AND DISCUSSION

Native Conversion Effects on SOC

When native soil was converted to agricultural land there was an average loss of 24 ± 6% of SOC based on 50 comparisons across Canada (Table 1). In the Chernozemic soils of the Prairie provinces, Newton et al. (1945) found that converting native grassland to arable land resulted in a loss of 22 ± 4% SOC, while Reinl (1984) found a loss of 24% of the native SOC for 72 farms in Alberta. In Ontario, Ellert and Gregorich (1996) reported that soils have lost 32 ± 9% of their original SOC across a broad range of soil types. In Podzolic soils of PEI and Quebec, there was 35% less SOC in cultivated soils relative to adjacent forests (Carter et al. 1998). Most losses of SOC occured within the first decade after implementing annual tillage and cropping (Mann 1986; Schlesinger 1986).

Although usually attributed to the physical breakdown of soil aggregates due to tillage, Janzen et al. (1997) suggested that the loss of SOC after plowing native land is the result of a combination of factors when one ecosystem is replaced with another. A major effect may be the fact that agriculture is in essence marketing carbon; carbon in various forms is removed from agricultural lands and sold for consumption.

However, SOC levels were not always lower in cultivated soils. In three soils in Quebec there was an average of 25% more SOC in one Gleysolic and two Brunisolic cultivated soils, relative to adjacent forest land (Carter et al. (1998), and Coote and Ramsey (1983) found that a sandy loam Melanic Brunisol had 21% more SOC than an adjacent forested soil in Ottawa. Although Carter et al. (1998) did not elaborate on the reasons for the greater SOC in the Gleysolic and Brunisolic cultivated soils, Coote and Ramsey (1983) stated that the Melanic Brunisol had had corn stover chopped and returned to the soil annually for many years, and therefore could have had larger inputs of residue carbon than the forest system.

Tillage Management and C Storage

The effects of tillage management on SOC were assessed in 23 tillage studies with 98 treatment comparisons and 1191 soil profiles (Table 2). A regression of SOC in NT versus that in **conventional tillage** (**CT**) for all treatments across Canada showed no net effect of tillage on SOC (Table 3). The storage rate of SOC in NT in Canada was calculated as 5 ± 16 g m^{-2} yr^{-1}. This is much lower relative to that determined by West and Post (2002) of 57 ±14 g m^{-2} yr^{-1} in their global analysis of 93 tillage comparisons.

There was an inverse relationship between SOC content and the effect of tillage on SOC, with gains due to adoption of NT occurring mainly at SOC levels of less than 45 Mg ha^{-1} (Fig. 1). The effectiveness of C storage in NT is reduced and can be negative when the background SOC content increases (Fig. 1). Paustian et al. (1997; Fig. 9), using data from 11 long-term studies in North America found a similar relationship. They speculated that the lower effectiveness of NT in soil with higher SOC levels was due to higher clay contents and higher soil moisture limiting growth potential and inputs of surface residues. However, soil erosion and redistribution over a prolonged period can also affect SOC storage under NT. VandenBygaart et al. (2002) concluded that soils that had lost SOC through soil erosion had a high potential to gain SOC when converted

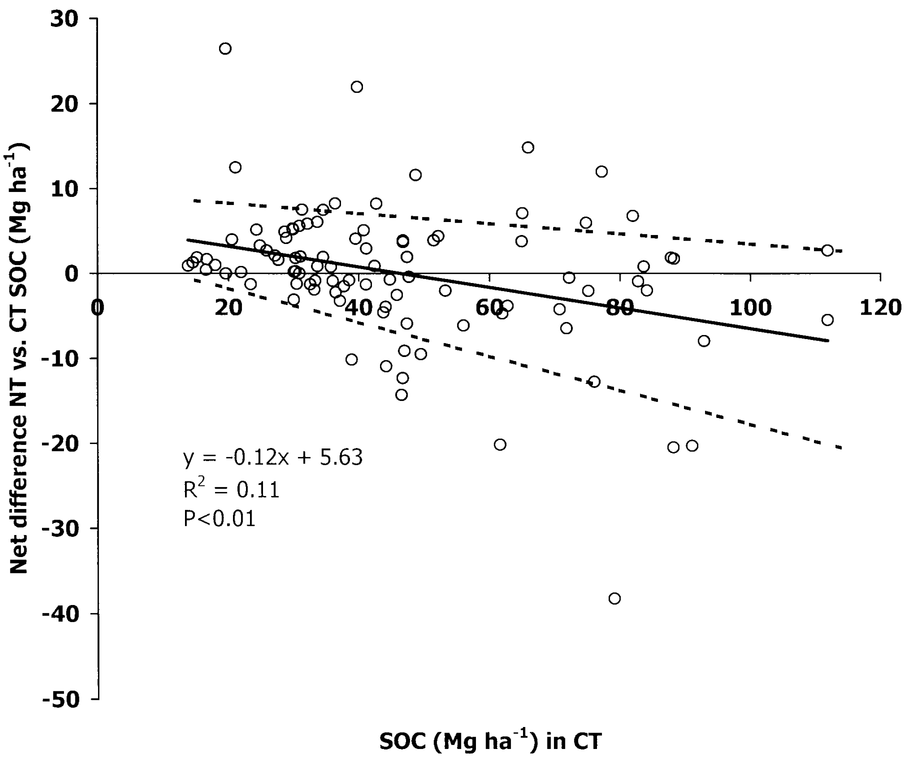


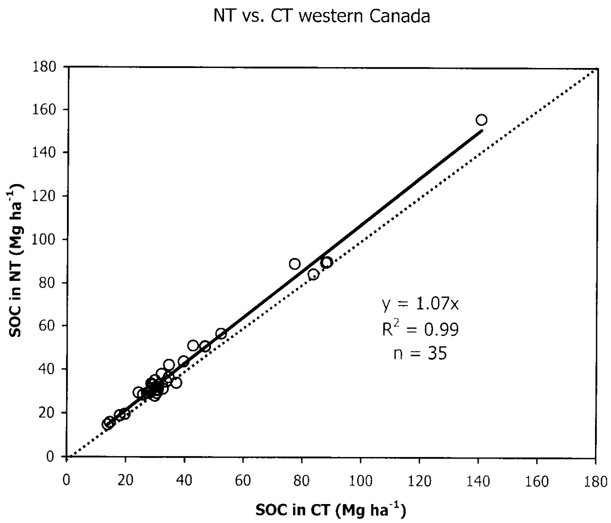
Fig. 1. Effect of SOC in CT on the difference in SOC between NT and CT for Canadian long-term field studies. Solid line is regression fit; dashed lines are upper and lower 95% confidence bands for the regression. One outlier removed (Yang and Kay 2001b). Data from Carter and Kunelius (1986), Winter et al. (1990), Angers et al. (1993a, 1995, 1997), Grant and Lafond (1994), Campbell et al. (1995a, 1996a, b, 2001a), Nyborg et al. (1995), Carter (1996), Franzluebbers and Arshad (1996), Larney et al. (1997), Dormaar and Carefoot (1998), Miller et al. (1999), Wanniarachchi et al. (1999), Carter and Sanderson (2001), Hao et al. (2001), Yang and Kay (2001a), Carter et al. (2002), VandenBygaart et al. (2002) and McConkey et al. (2003).

from CT to NT, whereas in depressional landscape positions (with high SOC from a history of soil deposition) the potential to gain SOC was lower when converted to NT, with some soils even losing SOC.

The effect of tillage on SOC (NT vs. CT) was assessed based on soil classification (Table 3). Chernozemic soils of the Canadian Prairies showed a greater ability to store SOC under NT relative to CT than other soil orders, especially in the more humid Chernozemic Great Groups (DBC and BlC)(Table 3). Only 4 of 33 comparisons had lower SOC levels under NT than CT when the mean annual precipitation was less than 600 mm, and 28 of these 33 treatment pairs were in soils of the Chernozemic order. There was a much lower storage potential and greater uncertainty for soils in the Gleysolic and Podzolic orders in cooler, moister climates (Table 3). In Humic Gleysols, in which SOC is greater than 2.0% in the A horizon (Agriculture Canada Expert Committee on Soil Survey 1998) SOC was generally lower under NT than under CT (Table 3). Angers et al. (1997) evaluated SOC storage in cool, humid climates of eastern Canada, and concluded that there tended to be lower SOC at or below the plow layer in NT soils than in CT soils, a trend also observed by VandenBygaart et al. (2002). In cooler, more humid climates there may be a reduction in the rate of decomposition of crop residues that are buried after soil inversion by the moldboard plow (Angers et al. 1997). This may limit the ability of NT soils to store SOC in cool, moist climates, since residues are no longer buried after converting to NT, resulting in a net loss of SOC (VandenBygaart et al. 2002).

As a consequence of these trends, we subdivided the dataset based on whether the study was conducted in western or eastern Canada (i.e., Ontario-Manitoba border as boundary)(Table 3, Fig. 2). In western Canada, the rate of SOC storage in NT soils was 32 ± 15 g m^{-2} yr^{-1} (Table 3), whereas in eastern Canada the rate of storage was –7 ± 27 g m^{-2} yr^{-1} (Table 3). These data could also be segregated based on temperature and precipitation: for western Canada all studies had a **mean annual precipitation** (**MAP**) of less than 550 mm, while eastern Canada studies had a MAP of at least 800 mm. All but 4 of the 35 comparisons showed a gain of SOC when the MAP was less than 550 mm, whereas only 23 of 63 comparisons in eastern Canada where the MAP was greater than 800 mm showed gains in SOC in NT. Western Canadian studies had mean annual temperatures of 5°C or less, whereas eastern Canadian studies were mostly in areas with a MAT of 4°C or greater. A number of factors may be responsible

(a)



(b)

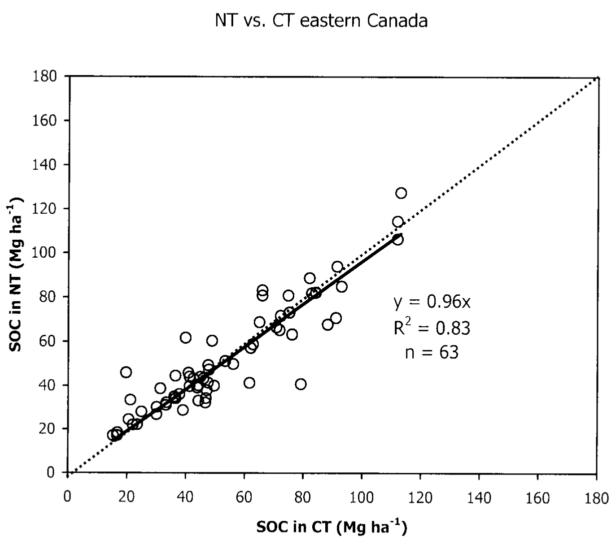


Fig. 2. SOC in NT relative to CT for studies conducted in (a) western Canada and (b) eastern Canada. Solid line is regression; dashed line is 1:1. Outliers removed from Yang and Kay (2001b). Data from Carter and Kunelius (1986), Winter et al. (1990), Angers et al. (1993a, 1995, 1997), Grant and Lafond (1994), Campbell et al. (1995a, 1996a, b, 2001a), Nyborg et al. (1995), Carter (1996), Franzluebbers and Arshad (1996), Larney et al. (1997), Dormaar and Carefoot (1998), Miller et al. (1999), Wanniarachchi et al. (1999), Carter and Sanderson (2001), Hao et al. (2001), Yang and Kay (2001a), Carter et al. (2002), VandenBygaart et al. (2002), McConkey et al. (2003).

for the apparent lower SOC storage ability of NT in eastern Canada:

1. Soils of eastern Canada are usually moldboard plowed, and this inverts and mixes the residues deep in the soil (15–30 cm), whereas in western Canada, tillage is much shallower (10–15 cm) and there is no inversion. In cooler, more moist soils of eastern Canada, aeration can be limiting at depth, reducing decomposition of the buried residues (Angers et al. 1997); converting to NT may eventually lead to the decomposition of these previously buried crop residues (VandenBygaart et al. 2002);
2. Moisture levels near the soil surface (where residues are concentrated in NT systems) are likely greater through the year in eastern Canada, thus favouring greater decomposition of surface crop residues;
3. Cropping systems of eastern Canada are often corn (*Zea mays* L.)-based, whereas in western Canada they tend to be wheat-based. Residue quality differs in these systems, with cereals having higher lignin contents (16 to 24%) than corn (11 to 16%) (Paustian et al. 1997); higher lignin content slows decomposition of organic matter (Stevenson 1994).
4. Tillage effects on crop yield can differ between corn-based and wheat-based systems. In corn-based systems yield effects under NT relative to CT are variable, with some studies showing only slight improvements in yield in NT (Hussain et al. 1999; Karunatilake et al. 2000), while others have shown negative or little effect of NT on grain yields (Ball-Coelho et al. 1998; Linden et al. 2000). In western Canada, significant yield advantages in favour of NT in wheat-based systems have been shown to occur in the Black soil zone (Larney et al. 1994; McAndrew et al. 1994) and in Gray Luvisols (Arshad et al. 2002), with little or no differences between NT and CT in the drier Dark Brown and Brown soil zones (Brandt 1992; McConkey et al. 1996). Greater crop yields under NT relative to CT in some areas of western Canada may contribute to greater SOC contents in NT systems.
5. Soil organisms may vary in population and diversity between eastern and western Canada. For example, nightcrawler earthworms (*Lumbricus terrestris* L.) have higher populations in NT soils relative to CT (Kladivko et al. 1997; VandenBygaart et al. 1998), but they are not present in soils of western Canada (Clapperton et al. 1997). Assimilation of surface residues into the soil by nightcrawler earthworms may enhance residue decomposition, thus limiting SOC storage in eastern Canadian soils under NT.

We also assessed the effect of cropping practices on the ability of the soil to store SOC under NT (Table 4). Corn and wheat under monoculture had the highest storage rates under NT relative to CT. Although the uncertainty level is high, barley (*Hordeum vulgare* L.), either in rotation or grown continuously, tended to show the lowest rates of storage under NT, and the data suggest that it can result in a net loss of SOC (Table 4). No-till conversion in fallow-wheat systems resulted in storage rates of 14 ± 13 g C m^{-2} yr^{-1}. This is higher than the rate of 2 ± 19 g C m^{-2} yr^{-1} determined by West and Post (2002) in their global analysis of long-term studies, in which they suggest that C storage does not occur in wheat-fallow systems when moving from CT to NT. However, their analysis included some of the data used in this review, suggesting that data from the Prairie Provinces skews the global data towards lower SOC storage rates. Our analysis of these data suggests that SOC storage can be

Table 4. Effect of cropping practices on SOC in NT relative to CT in Canadian long-term field studies

Cropping practice with NT	Net difference (Mg ha^{-1})	Relative difference (%)	Storage rate (g C m^{-2} yr^{-1})	Regression coefficient[z]	Duration (yr)	Comparisons (*n*)	Soil profiles (*n*)	References[y]
Wheat-fallow	1.3 ± 1.7	5.7 ± 5.9	14 ± 13	1.04 ± 0.08†	14.0 ± 3.0	10	184	1-4,6,8,10
Wheat w/ fallow at most every 3rd yr	2.3 ± 3.3	7.8 ± 11.3	23 ± 33	1.07 ± 0.18	10.0 ± 0.0	4	32	6
Continuous corn	2.6 ± 3.4	3.9 ± 6.0	26 ± 40	1.05 ± 0.07	11.3 ± 4.5	10	132	15,17,19,21,22
Continuous wheat	3.4 ± 3.8	8.5 ± 5.2	53 ± 80	1.14 ± 0.09*	10.7 ± 2.4	7	111	1-4,6,19
Continuous barley	–0.9 ± 4.5	1.7 ± 7.1	–37 ± 78	0.97 ± 0.06	8.5 ± 2.1	11	344	5,19
Corn-wheat-soybean	0.0 ± 11.68	2.8 ± 23.2	–3 ± 70	1.01 ± 0.09	15.4 ± 0.9	42	76	14,16,23
Barley in variable rotation	–1.6 ± 4.3	0.7 ± 7.7	–16 ± 57	0.93 ± 0.07	7.0 ± 1.7	4	68	18,19
Unknown[x]/variable rotation	4.5 ± 5.7	6.7 ± 8.4	79 ± 76	1.09 ± 0.08*	6.4 ± 1.8	6	172	7,9,11-13
All rotation[w]	0.6 ± 3.1	3.6± 6.1	7.3 ± 20.3	1.02 ± 0.06	13.4 ± 1.0	66	532	1-4,6,8-14,16, 18,19,23
Monoculture[v]	1.2 ± 1.6	3.8 ± 2.5	2.8 ± 26.7	1.01 ± 0.04	9.8 ± 1.3	28	587	1-6,15,17,19, 21,22

[z]Derived by linear regression as the slope between SOC in management treatment versus the SOC in the control treatment and forced through zero.
[y]Campbell et al. (1996a) (1), Campbell et al. (1996b) (2), Campbell et al. (1995a) (3), Larney et al. (1997) (4), Nyborg, et al. (1995) (5), Campbell et al. (2001a) (6), Grant and Lafond (1994) (7), McConkey et al. (2003) (8), Hao et al. (2001) (9), Miller et al. (1999) (10), Dormaar and Carefoot (1998) (11), Franzluebbers and Arshad (1996) (12), Carter (1996) (13), Yang and Kay (2001a) (14), Wanniarachchi et al. (1999) (15), VandenBygaart et al. (2002) (16), Carter et al. (2002) (17), Carter and Sanderson (2001) (18), Angers, et al. (1997) (19), Carter and Kunelius (1986) (20), Angers et al. (1995) (21), Winter et al. (1990) (22), Yang and Kay (2001b) (23).
[x]Not listed or unclear from publication.
[w]Includes green manure-w-w rotation from Campbell et al. (2001a).
[v]Includes Carter and Kunelius 1986 cont. potato.
†,* denote coefficient significantly different than 1 at $P < 0.10$ and $P < 0.05$ respectively.

achieved, although at low rates, in wheat-fallow systems converted to NT in cool, semi-arid climates such as those in the Canadian Prairies (Table 4).

Crop Management and C Storage

We compiled 87 comparisons over a total of 1669 treatment years from studies assessing the effect of crop rotation on SOC, with most (96%) of the comparisons located in western Canada (Table 2).

Regardless of tillage treatment, more frequent fallowing resulted in a lower potential to gain SOC (Fig. 3). When fallow was removed and wheat grown continuously, SOC was stored at a rate of 15 ± 6 g C m^{-2} yr^{-1} (Fig. 4, Table 5). Replacement of fallow with wheat grass (*Agropyron cristatum* L. or *A. trichophorum*) may also result in a gain in SOC (Table 5). This reflects the reduced residue C inputs during fallow periods and increased mineralization of SOC due to higher soil moisture in fallow (Campbell et al. 2001a). Campbell et al. (2001b) estimated that the Brown and Dark Brown Chernozems of the Prairie Provinces store 7.5 and 16.5 g C m^{-2} yr^{-1} of SOC, respectively, due to reduction in summer fallow.

Replacing wheat with flax (*Linum usitatissimum* L.) resulted in lower SOC at a rate of –15 ± 2 g C m^{-2} yr^{-1} (Table 5). Flax contributes smaller amounts of residue with higher lignin contents to the soil than wheat, and flax straw tends to be more easily blown off fields after harvest than wheat straw (Campbell and Zentner 1993).

When hay is included in rotation with fallow and wheat, there is a potential to gain substantial amounts of SOC (Fig. 5) at a rate of 22 ± 19 g C m^{-2} yr^{-1} (Table 5). This reflects the greater inputs of above- and below-ground residues associated with hay (Campbell et al. 1998).

Replacement of fallow with legume "green manures" such as lentil (*Lens culinaris* M.) and red clover (*Trifolium pratense* L.) appears to be an effective C storage practice (Fig. 6), with rates of C storage of 15 ± 11 g C m^{-2} yr^{-1} (Table 5). Plowing legume crops as green manures into the soil results in large inputs of mineralizable N to the soil, which help to maintain higher C levels (McGill and Bailey 1999).

Replacing wheat with fall rye (*Lolium perenne* L.) in fallow-wheat-wheat rotations can increase storage of SOC, but at lower rates and with high variability (10 ± 14 g C m^{-2} yr^{-1}) (Table 5). Systems with fall rye (cereal) included in a cropping sequence make efficient use of N during the growing season, which can increase SOC relative to fallow-spring wheat systems (Campbell and Zentner 1993).

When straw is not removed, SOC storage occurs, although the gains are small (12 ± 9 g C m^{-2} yr^{-1}) (Table 5, Fig. 7). Campbell et al. (1991c) suggested that the lower-than-expected effect of straw retention on SOC might be due to roots contributing more to SOC storage than residues in these systems, and increases in residues from straw incorporation, which widen the C:N ratio and increase microbial decomposition of humus in the soil.

Although the level of uncertainty is high, including legumes such as alfalfa (*Medicago sativa* L.) or red clover in rotation with corn can result in large gains in SOC content relative to corn grown in monoculture (44 ± 28 g C m^{-2} yr^{-1}) (Table 5). Gregorich et al. (2001) found that SOC below the

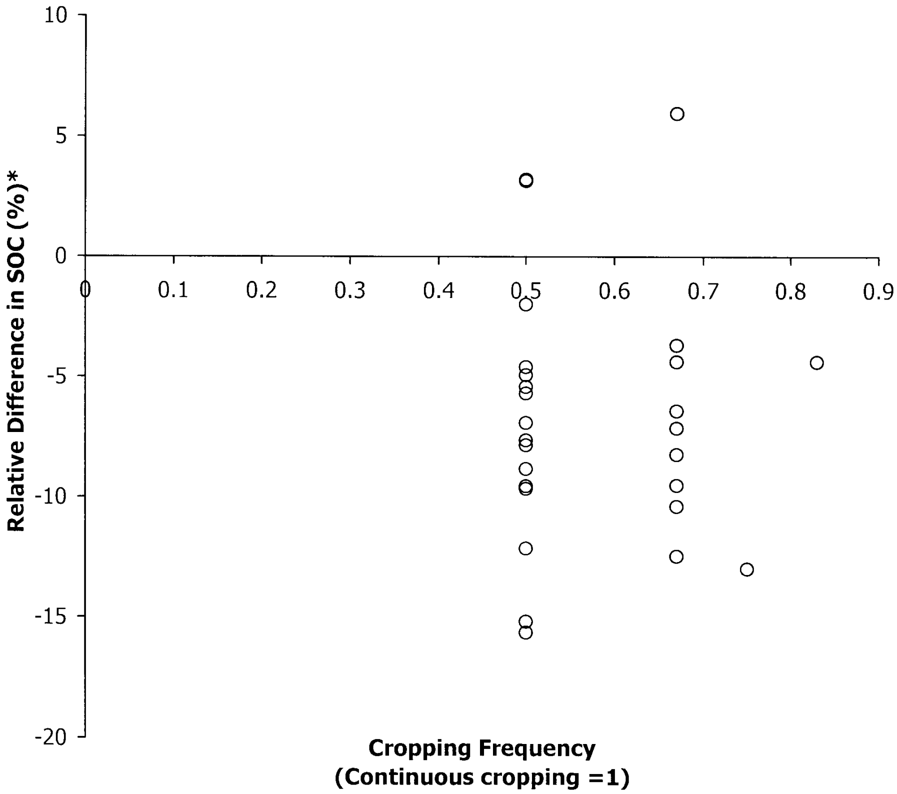


Fig. 3. Effect of cropping frequency on SOC. *Relative difference in SOC normalized to SOC content under continuous cropping in each study. Only data for N and P fertilized plots are reported. F-W = 0.5; F-W-W = 0.67; F-W-W-W = 0.75; F-W-W-W-W = 0.83. Data from Campbell et al. (1991b, 1992, 1995, 1996a, b, 1998, 2000a, 2001), Larney et al. (1997), Bremer et al. (1994, 2002), Biederbeck et al. (1998), and Izaurralde et al. (2001).

plow layer was greater in legume-based rotations than under corn in monoculture. They also observed that the legume-based rotations contained much greater amounts of aromatic C content (a highly biologically resistant form of carbon) below the plow layer than continuous corn, suggesting that residue quality plays an important role in SOC storage.

Fertilizer Inputs and SOC

The average annual C storage rate for soils fertilized with inorganic fertilizer, regardless of the level of input, was 23 ± 13 g C m^{-2} yr^{-1} (Table 6), which is similar to the average rate of 29 g C m^{-2} yr^{-1} with inorganic fertilizer found by Conant et al. (2001) for grassland soils around the world, and 27 g C m^{-2} yr^{-1} rate with inorganic fertilizer in no-till soils from 15 comparisons in the U.S. (Franzluebbers and Steiner 2002). There was a weak, linear relation between change in SOC and inputs of inorganic fertilizer (Fig. 8a). Paustian et al. (1997) found a similar general relationship in reviewing 20 studies from around the world. When we consider situations where less than 50 kg ha^{-1} yr^{-1} N was applied there was a much stronger relationship between the change in SOC and N applied (Fig. 8b). If N use by the plant is reflected by SOC content, perhaps lower rates of N fertilization result in more efficient use of N than higher rates of application. Paustian et al. (1997) suggested that, in a broad sense, C:N ratios are relatively similar across a large range of agricultural soils, and that, if the inputs of these two elements are somewhat out of balance, then the efficiency of SOC storage may be reduced. This is reflected in the lack of response in SOC storage to straw additions (Fig. 7).

Not surprisingly, addition of organic fertilizers, such as manure, sewage sludge and wood chips is an effective means to increase SOC in agricultural soils (Table 6). Most studies on the effect of organic fertilizers on SOC report on a concentration basis, with few reporting on a volumetric basis (Table 2). The rate of annual input of organic amendments was related to the relative difference in SOC regardless of the type of additions, and shows that adding exogenous carbon to the land can result in significant amounts of C being stored in soil.

Example of Use of IPCC Guidelines Model for SOC Stocks and Change in SOC

By deriving linear regressions relating baseline SOC and treatment SOC from our database, and forcing the regression line through the origin, the derived coefficients can be used as coefficients in the IPCC model for determining SOC stocks. Although the IPCC model is intended for broad-based estimates of carbon stocks at national levels, variants of the model can be applied at the field- or farm-scale using coefficients and uncertainty levels derived from the database. For example, if a cash-crop farmer, located in the Brown Chernozemic Soil Zone of Saskatchewan (native SOC in adjacent prairie is 50 Mg ha^{-1} to 30 cm) is currently using a fallow-wheat rotation in conventional tillage, and removes straw for off-farm sale, the SOC stock can be estimated. Soil $Carbon_{native}$ is 50 Mg ha^{-1}, the Base factor from Table 1 is 1 – (0.24 ± 0.06) = 0.76 ± 0.06, and the Input fac-

Table 5. Effect of cropping practices and rotations on SOC in Canadian long-term field studies

Cropping practice	Net difference (Mg ha^{-1})	Relative difference (%)	Storage rate (g C m^{-2} yr^{-1})	Regression coefficient[z]	Average Duration (yr)	Comparisons (n)	Soil profiles (n)	Reference(s)[y]
Fallow removed; replaced w/ wheat; (i.e. cont. wheat)	2.2 ± 0.7	6.7 ± 2.2	15 ± 6	1.06 ± 0.02***	23.0 ± 8.8	19	263	1-8,10,11
Fallow-wheat system; replaced w/ cont. wheat grass[x]	2.3 ± 0.7	10.6 ± 5.1	35 ± 19	1.09 ± 0.12	7.3 ± 2.6	3	30	9,11
Wheat replaced w/ flax	−2.4 ± 0.5	−7.2 ± 2.1	−15 ± 2	0.93 ± 0.05*	16 ± 1.6	3	54	10,12,13
Hay[w] (variable freq.) w/ fallow-wheat system	4.0 ± 1.3	8.7 ± 4.3	22 ± 19	1.07 ± 0.04**	31.3 ± 4.5	9	133	4-6, 13
Legume green manure replacing fallow of f-w-w	2.3 ± 1.4	6.6 ± 4.0	15 ± 11	1.05 ± 0.04*	20.6 ± 8.2	7	94	4,6,7,9
Wheat replaced w/ rye in fallow wheat rotation	2.3 ± 3.4	7.7 ± 11.1	10 ± 14	1.07 ± 0.18	19.3 ± 6.6	4	51	8,10,12,13
Straw not removed	1.3 ± 1.0	2.7 ± 2.4	12 ± 9	1.01 ± 0.01	13.6 ± 4.2	13	464	6,14-16
Legumes in rotation with corn vs. cont. corn	14.4 ± 11.5	13.4 ± 9.8	44 ± 28	1.15 ± 0.20	30.0 ± 9.8	3	26	17,18
Wheat replaced w/ lentil in 2 yr rotation	1.9	5.4	n/a	n/a	approx. 20[v]	1	36	8

[z]Derived by linear regression as the slope between SOC in management treatment versus the SOC in the control treatment and forced through zero.
[y]Campbell et al. (1996a) (1), Campbell et al. (1996b) (2), Campbell et al. (1995) (3), Campbell, et al. (1991b) (4), Bremer et al. (1994) (5), Campbell et al. 1998 (6), Biederbeck et al. (1998) (7), Campbell et al. (2000a) (8), Campbell et al. (2000b) (9), Campbell and Zentner (1993) (10), Bremer et al. (2002) (11), Larney et al. (1997) (12), Biederbeck et al. (1984) (13), Nyborg et al. (1995) (14), Solberg et al. (1997) (15), Dormaar and Carefoot (1998) (16), Gregorich et al. 2001 (17), Yang and Kay (2001b) (18).
[x]Cut for hay.
[w]Alfalfa-grass mixture cut for hay.
[v]Mean of six sampling periods between 10 and 30 yr after experiment was initiated.
*, **, *** denote coefficient significantly different than 1 at $P < 0.05$, $P < 0.01$, $P < 0.001$ respectively.

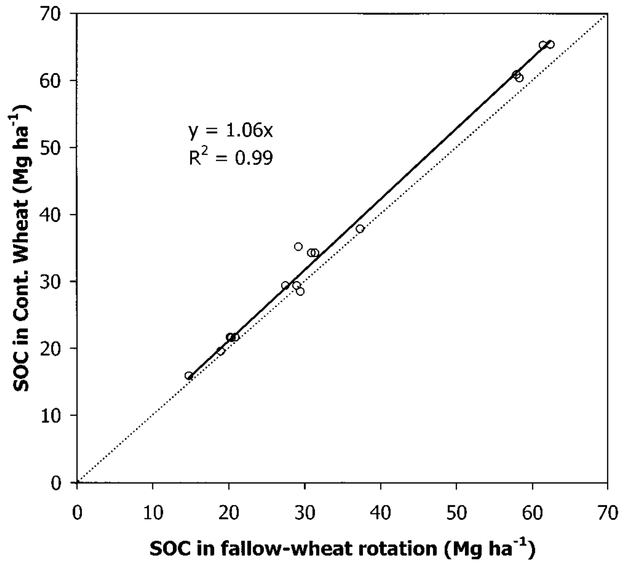


Fig. 4. Comparison of SOC content in continuous wheat relative to fallow-wheat rotation. Solid line is regression; dashed line is 1:1. Data from Campbell, et al. (1991b, 1995, 1996a, b, 1998, 2000a), Campbell and Zentner (1993), Bremer et al. (1994, 2002), Larney et al. (1997) and Biederbeck et al. (1998).

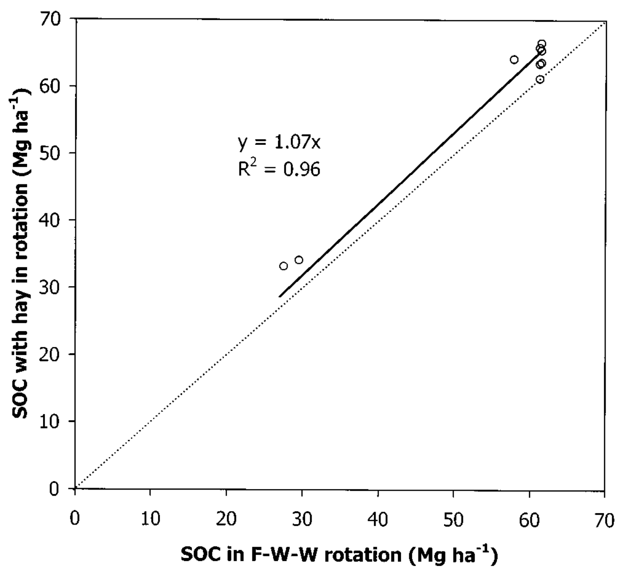


Fig. 5. Comparison of SOC content with hay in rotation relative to F-W-W rotations. Solid line is regression; dashed line is 1:1. Data from Biederbeck et al. (1984), Campbell et al. (1991b, 1998) and Bremer et al. (1994).

tor from Table 5 is 1 – (1.01 ± 0.01) = 0.99 ± 0.01 since straw was removed:

$$\text{Soil Carbon}_{\text{managed}} = 50 \times [0.76 \pm 0.06] \times 1.0 \times [0.99 \pm 0.01].$$

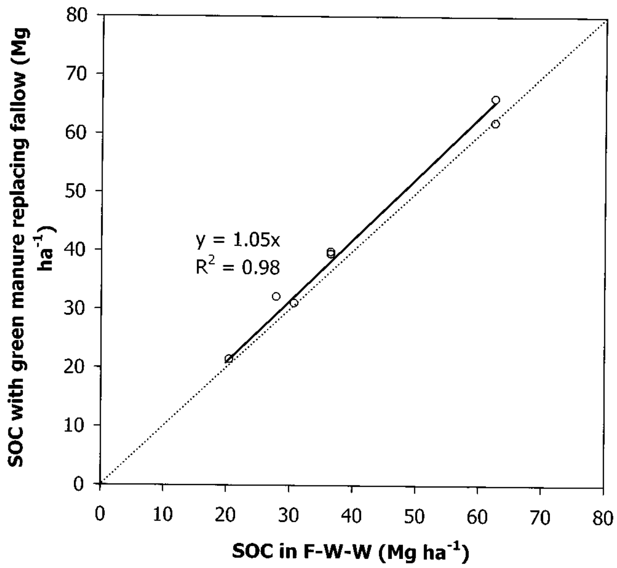


Fig. 6. Comparison of SOC content with green manure crop replacing fallow relative to F-W-W rotations. Solid line is regression; dashed line is 1:1. Data from Campbell et al. (1991b, 1998, 2000b) and Biederbeck et al. (1998).

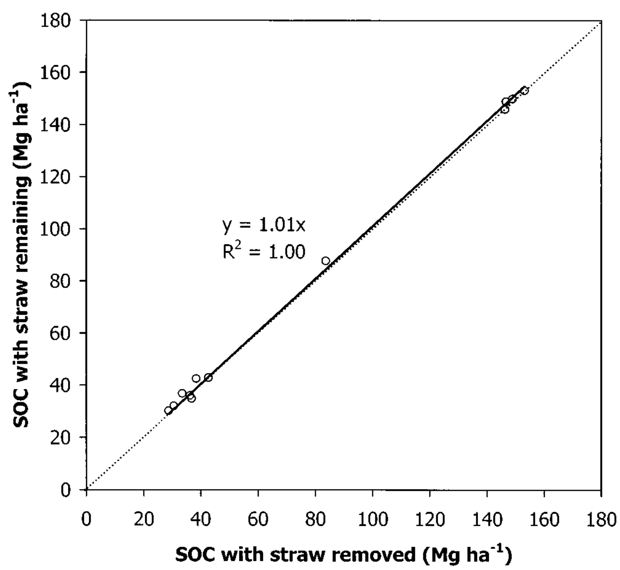


Fig. 7. Comparison of SOC content with straw retention on the soil surface relative to straw removed. Solid line is regression; dashed line is 1:1. Data from Nyborg et al. (1995), Solberg, et al. (1997), Campbell et al. (1998) and Dormaar and Carefoot (1998).

The errors are combined by multiplicative error propagation (IPCC 2000):

$$U_{total} = \sqrt{U_1^2 + U_2^2 + \ldots U_n^2} \tag{3}$$

where U_{total} is the percentage uncertainty in the product of the quantities (half the 95% confidence interval divided by the total expressed as a percentage), and U_i are the percentage uncertainties associated with each of the terms. This gives a managed SOC level of 38 ± 3 Mg ha^{-1}.

If the soil management is changed from conventional tillage to no-till and if fallow is replaced so that wheat is in monoculture, and mineral N is added at varying rates annually, the new SOC stock is:

$$\text{Soil Carbon}_{new} = \text{Soil Carbon}_{managed} \times \text{Tillage}_{new} \times \text{Input}_{rotationnew} \times \text{Input}_{fertilizernew} \tag{4}$$

where Tillage_{new} is the coefficient applied for a change in tillage practice, $\text{Input}_{rotationnew}$ is the coefficient to apply for the new rotation relative to the initial rotation, and $\text{Input}_{fertilizernew}$ is the coefficient to apply for fertilizer application. That is, with coefficients from Tables 3, 5 and 6:

$$\text{Soil Carbon}_{new} = (38 \pm 4 \text{ Mg ha}^{-1}) \times (1.07 \pm 0.02) \times (1.06 \pm 0.02) \times (1.06 \pm 0.03)$$

yields a new SOC level of 46 ± 5 Mg ha^{-1}, or a net gain of about 8 Mg ha^{-1} of C in the new system.

We can also estimate over what time period the change can be expected by determining the mean duration over which the experimental coefficients were derived:

$$\text{Mean duration} = (\text{Duration}_{tillage} + \text{Duration}_{rotation} + \text{Duration}_{fertilizer} \ldots)/n \tag{5}$$

Where n is the number of coefficients used to determine the SOC stock. From Tables 3, 5 and 6, the change in SOC stock for the above example can be expected to occur within a duration of:

$$[(12.3 \pm 2.3) + (23.0 \pm 8.8) + (23.2 \pm 4.5)]/3$$

or 19.5 ± 9 yr.

Limitations, Gaps and Uncertainties

Caution is warranted in interpreting studies comparing SOC in native land to adjacent cultivated soils. Bulk density was determined only in the studies by Ellert and Gregorich (1996) and Carter et al. (1998) (Table 1). The relative differences in SOC may be less accurate on a concentration basis since bulk density can vary considerably between the native and cultivated sites. Soil organic carbon generally becomes diluted throughout the A_p horizon due to plowing of the cultivated land, which is a problem for interpretation of the changes in SOC after conversion, unless the entire plow layer is sampled along with the bulk density. Most studies compared cultivated plots with adjacent native soils located in different locations, further compromising the accuracy, since the initial SOC levels may have been different when the soils were initially cultivated.

Studies conducted in western Canada showed a strong potential to increase SOC storage when soils were converted to NT from CT. A majority of these studies (31 of 35 comparisons) measured the differences in SOC in the top 15 cm. In eastern Canada, all but four comparisons (59 of 63

Table 6. Effect of organic and inorganic fertilizers on SOC in Canadian long-term field studies

Practice	Net difference (Mg ha^{-1})	Relative difference (%)	Storage rate (g C m^{-2} yr^{-1})	Regression coefficient[z]	Duration (yr)	Comparisons (*n*)	Soil profiles (*n*)	References[y]
N application at varying rates	4.4 ± 2.6	7.0 ± 2.8	23 ± 13	1.06 ± 0.03***	23.2 ± 4.5	33	836	1–12
organic fertilizer (varying types at varying rates)[x]	n/a	28.2 ± 11.0	n/a	1.15 ± 0.16†	13.1 ± 7.0	17	146	12–19

[z]Derived by linear regression as the slope between SOC in management treatment versus the SOC in the control treatment and forced through zero.
[y]Nyborg et al. (1998) (1), Nyborg et al. (1999) (2), Malhi et al. (1997) (3), Solberg, et al. (1997) (4), Liang and Mackenzie (1992) (5), Gregorich et al. (1996) (6), Campbell et al. (2000b) (7), Campbell et al. (1998) (8), Dormaar and Carefoot (1998) (9), Malhi et al. (2002) (10), Campbell et al. (1991b) (11), Izaurralde et al. (2001) (12), Pare et al. (1999) (13), N'dayegamire and Angers (1993) (14), Zebarth et al. (1999) (15), N'dayegamire and Cote (1989) (16), Dormaar and Sommerfeld (1986) (17), Bremer et al. (1994) (18), Grant et al. (2001) (19).
[x]Data on concentration basis.
†,*** denote coefficient significantly different than 1 at $P < 0.10$ and $P < 0.001$ respectively.

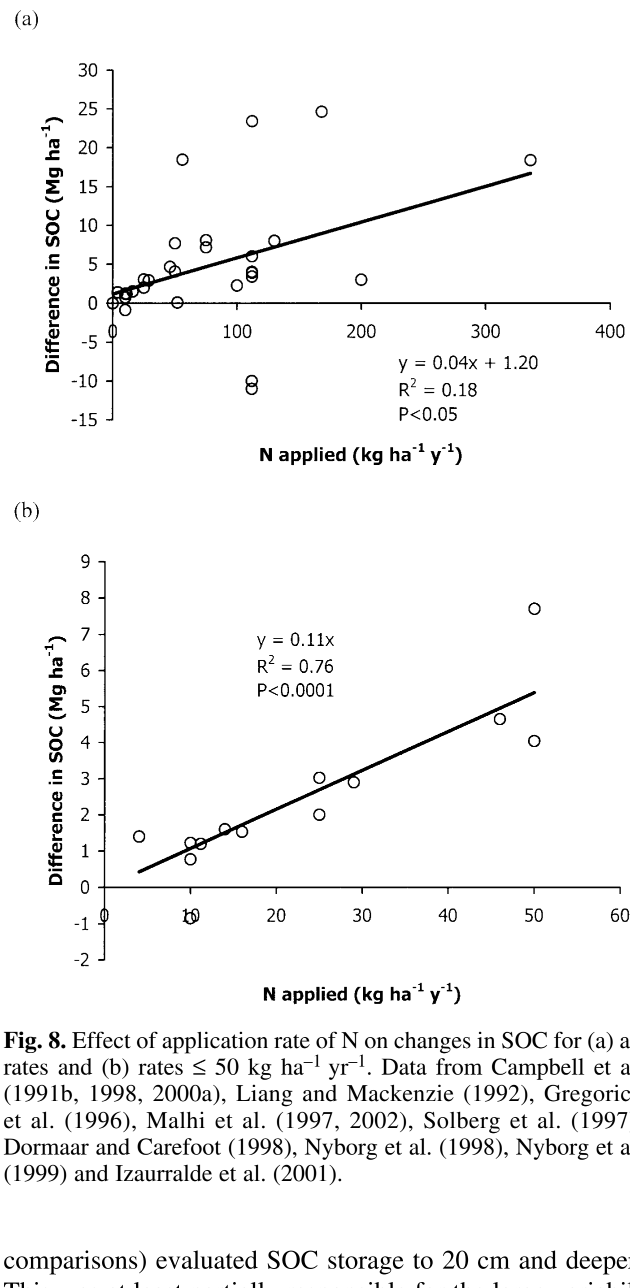


Fig. 8. Effect of application rate of N on changes in SOC for (a) all rates and (b) rates ≤ 50 kg ha^{-1} yr^{-1}. Data from Campbell et al. (1991b, 1998, 2000a), Liang and Mackenzie (1992), Gregorich et al. (1996), Malhi et al. (1997, 2002), Solberg et al. (1997), Dormaar and Carefoot (1998), Nyborg et al. (1998), Nyborg et al. (1999) and Izaurralde et al. (2001).

comparisons) evaluated SOC storage to 20 cm and deeper. This was at least partially responsible for the large variability in the changes in SOC in eastern Canada (Fig. 2b), as variability has been shown to increase with depth of sampling for SOC (Campbell et al. 2000b; Ellert et al. 2002; Yang and Kay 2001; Wanniarachchi et al.1999). Consequently, variability in SOC storage measurements can mask true changes as a result of a treatment. If the variability at depth cannot be explained, there is less confidence in attributing the change in SOC storage to tillage management. Yet we should not simply discount the measurements at lower depths.

We must also be cautious when extrapolating results from controlled, long-term studies to the farmer's fields and landscapes. Most long-term research occurs in relatively small plots that are usually located in level landscapes to control and minimize the effects of other factors such as topography and soil erosion. Furthermore, many farmers have a diverse history of soil and crop management due to the reality of changing markets and prices for their products. This diverse history of management has an effect on SOC and may influence future changes in SOC. For example, if a farmer has installed tile drains in a poorly drained soil, say 5 yr prior to sampling, there could be a concomitant decrease in SOC due to better conditions for microbial decomposition of the soil organic matter. The decrease in SOC may still be occurring when the farmer decides to make a change in crop or tillage management that has been shown to increase SOC from long-term research plots. Therefore, any positive effect on the SOC content after the change may be masked by the continued decline in SOC content due to better drainage on the field. Thus, the change in management may not result in a net gain in SOC after a number of years. Instead the management practices may have simply slowed the decomposition process associated with tile drainage, and the net result may still be a loss in SOC. Similar scenarios could occur if there was a diverse history of C inputs and other management. For example, if a farmer no longer applies manure after applying it for several years and then omits summer fallow, or a farmer no longer plows in green manures and this occurs simultaneously with the introduction of NT.

Canola is a major crop in the sub-humid regions of the Canadian Prairies (Clayton et al. 2000). However, there are few data on the direct effects of canola production on SOC levels. Since about 3.5 Mha of land are cropped to canola in a year in the Canadian Prairies (Census of Agriculture

2001), there is a need to characterize the effects of canola on SOC dynamics and storage.

CONCLUSIONS

Management of soils in Canadian agricultural systems has a significant effect on SOC storage. However, the effectiveness of different management practices varies across the country, and under certain management conditions. For example, conversion to no-till from conventional tillage was most effective in increasing C storage in the Chernozemic soil zones of the Canadian Prairies, but did not increase SOC storage in moister soils of eastern Canada, suggesting that climate affects the ability of soils to store SOC under NT. Replacing fallow with wheat generally resulted in an increase in SOC storage, but replacement with flax can result in a net loss in SOC. Including hay in rotation with wheat was an effective practice for increasing SOC storage. Addition of inorganic and organic fertilizers generally resulted in an increase in SOC, while straw removal did not affect SOC levels.

Developing a database of studies from Canada allowed us to derive coefficients that could be used in the IPCC model for soil C stocks, along with uncertainty levels in the estimates. Using a modified version of the IPCC model, the SOC response to changes in management practices within a given system was estimated.

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