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Soil and Crop Management and the Greenhouse Gas Budget of Agroecosystems in Canada

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ABSTRACT

In 1990, primary agriculture contributed 10% of the anthropogenic greenhouse gas emissions in Canada while the whole agriculture and agri-food sector contributed 15%. By 2010, greenhouse gas emissions from primary agriculture are expected to have increased by about 8 Tg CO_2 equivalent. In order to examine the potential of this sector to reduce its emissions, we investigated the effects of several carbon (C) sequestration strategies on the greenhouse gas budget. We estimated, using the Century model (April 1999 version), the change in soil carbon associated with the implementation of four management practices: 1) An increase in the acreage of no-till farming from 14% in 1996 to 30% by 2010 would result in an average sequestration of 1.15 Tg yr^{-1} C. 2) A reduction in the acreage of cropland under summer fallow by 2.8 million hectares (Mha) for the Chernozemic soils in the Prairies would result in an increase in soil C of 0.46 Tg yr^{-1} C. 3) An increase in N fertilizer by 50% would increase soil C storage by another 0.26 Tg yr^{-1} C. 4) An increase in the acreage of perennial grass cover from 15% to 19% would increase soil carbon sequestration by 0.60 Tg yr^{-1} C. These changes in carbon storage, which are based on a 20-year average, are equal to 2.5 Tg yr^{-1} C. Such changes are equivalent to reducing agricultural emissions by 9.2 Tg yr^{-1} CO_2, which is about 80% of the amount required by the primary agriculture sector to meet its part of the Kyoto commitment. Considering that these estimates were made on only about two thirds of the croplands and for only four mitigation measures, increased C storage in agricultural soils appears to be a viable approach to help Canada meet part of its international commitment. However, emissions of other greenhouse gases associated with these mitigation measures could negate a substantial part of the gains obtained from carbon sequestration.

INTRODUCTION

International concerns about climate change have caused many countries to commit to a reduction of their greenhouse gas emissions. This can be achieved by either reducing the sources of greenhouse gases or by removing CO_2 from the atmosphere by increasing the C pool in vegetation and/or soils. The latter is a particularly promising area, considering that agricultural soils in Canada have lost more than 1 Petagram (Pg) of carbon since cultivation began (Dumanski et al., 1999; Smith et al., 2000). It is then reasonable to investigate the potential of agricultural soils for sequestering C and to determine how the agriculture sector could help Canada meet its commitment to reduce greenhouse gas emissions to 6% below the 1990 level by 2010.

It is impossible to accurately measure all the changes in C in agricultural soils. Hence a modeling approach is required. The Century model, which is described by Parton et al. (1987, 1989 and 1993), simulates the long-term dynamics of C, N, P and S for various crop-soil systems. It accounts for agricultural management practices such as fertilizer application, tillage, grazing and organic matter addition on various soil types. The objective of this paper is to examine the influence of increased area of no-till, reduction in the area of summer fallowing, conversion of cultivated land into perennial grass cover and increase use of fertilizer on the soil C sequestration potential of agricultural soils in Canada.

Table 1. Greenhouse gas emissions from Canadian agroecosystems with and without inputs.

	1981	1986	1991	1996
	GHG emitted without inputs (Tg CO_2 equivalent)			
CO_2	8	7	5	2
CH_4	22	20	20	23
N_2O	27	25	26	31
Total	57	52	51	56
	GHG emitted with inputs (Tg CO_2 equivalent)			
CO_2	30	28	26	26
CH_4	22	20	20	23
N_2O	27	25	26	31
Total	79	73	72	80

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REVIEW

Table 1 summarizes the CO_2, CH_4 and N_2O emissions estimates from agroecosystems in Canada for the last four census years (Desjardins and Riznek, 2000). The CO_2 equivalent values are based on global warming potentials of 21 for CH_4 and 310 for N_2O (IPCC, 1996). If only CO_2 emissions from soils are included, that is agriculture without inputs, agriculture accounts for about 10% of the anthropogenic GHG emissions in Canada. If the CO_2 produced by fossil fuel used on-farm and the CO_2 emitted during the production of machinery and agrochemicals, plus the CO_2 emitted from soils are included, that is agriculture with inputs, then agriculture accounts for 13% of the greenhouse gas emissions. If all the sources from the Agriculture and Agri-Food sector are included, then the contribution is about 15%. It has been estimated that by 2010, the annual GHG emissions from agriculture without input (primary agriculture) will be 8 Tg C more than in 1990 (Kulshreshtha et al., 2000).

Restoring organic matter levels represents a potential sink for atmospheric CO_2. Recently, Bruce et al. (1999) estimated the potential carbon gain in agricultural soils in Canada to be about 200 Tg C over a 20-year period, if best practices were adopted on all available lands. Their estimate included a potential carbon sequestration of 0.2 Mg C ha^{-1} yr^{-1} on cultivated soils and pasture (41.3 Mha), 0.6 to 0.8 Mg C ha^{-1} yr^{-1} on restored grassland (1 Mha), and 0.1 to 1.0 Mg C ha^{-1} yr^{-1} on degraded soil (3.8 Mha).

METHODS

Increasing carbon uptake and carbon storage appears to be a reasonable approach for reducing greenhouse gas buildup. Several mitigation practices have been identified as possible means to increase carbon sequestration in agricultural soils (Janzen et al., 1999). In this paper the Century model is used to investigate the impact of four practices: 1) increased adoption of no-till, 2) reduced summer fallow, 3) improved nitrogen use and 4) a shift from cultivated land to more perennial grass cover. Changes in management are compared to a control simulation.

The Century model, a site-specific computer simulation model, makes use of simplified relationships of soil-plant-climate interactions to describe the dynamics of soil carbon and nitrogen in grasslands, crops, forests, and savannahs. It allows assessment of several agricultural management practices, including planting, fertilizer application, tillage, grazing and organic matter addition. It simulates above- and below-ground biomass production as a function of soil temperature, available water, and nutrients. Soil C is stabilized in slow cycling pools as a function of total amount of clay. Century has been extensively evaluated with reasonable success under contrasting soil, climatic and agricultural practices (Parton et al., 1982; Parton et al., 1987; Parton et al., 1989; Paustian et al., 1992; Angers et al., 1993; Monreal et al., 1995). Estimating soil organic carbon (SOC) dynamics for Canadian soils is a difficult task due to the diversity in soil, climate and agricultural practices. Several assumptions and simplifications were necessary to provide a reasonable estimation of SOC gain: 1) Simulations were performed on twenty-three of the Soil Landscape of Canada (SLC) polygons that had been used previously by Smith et al. (1997). A base simulation was carried out for each polygon, followed by additional runs for changes in management practices. Simulations were carried out from 1910 to 2020. The representative polygons were selected based on their distribution in the four major soil groups that make up the majority of the soils in Canada (Canada Soil Survey Committee, 1978). Soil properties such as bulk density, particle size distribution, pH, and initial organic carbon were obtained from the SLC database. Thirty-year monthly normals of temperature and precipitation, which were averaged from the three closest weather stations to each SLC polygon, were used for the simulations. Crop yield calibration in Century had already been completed for these SLC polygons and is documented in Smith et al. (1997; 2000). 2) For Western Canada, the SOC gains were calculated for Brown (5.3 Mha), Dark Brown (6.9 Mha) and Black (12.8 Mha) Chernozemic soil groups and for Eastern Canada the Gleysolic (2.7 Mha) soil group. This represents about 27.7 Mha of the 41.4 Mha of cultivated soils in Canada in 1990. 3) All simulations were performed in SLC polygons with medium textured soils. Loam textured soils make up the majority of soils found in croplands in Canada. 4) No-till percentages shown in Table 2 were applied evenly

Table 2. Actual and assumed adoption of no-till as a percentage of total agricultural area for each province in Canada.

	← Actual	→	← Assumed		→
Province	**1990**	**1995**	**2000**	**2005**	**2010**
			No-Till (%)		
Atlantic	2	2	2	2	2
Quebec	3	4	7	9	11
Ontario	4	15	20	20	20
Manitoba	4	8	12	15	20
Saskatchewan	10	20	30	35	38
Alberta	3	9	17	23	28
British Columbia	5	9	13	16	20
Canada	7	14	22	26	30

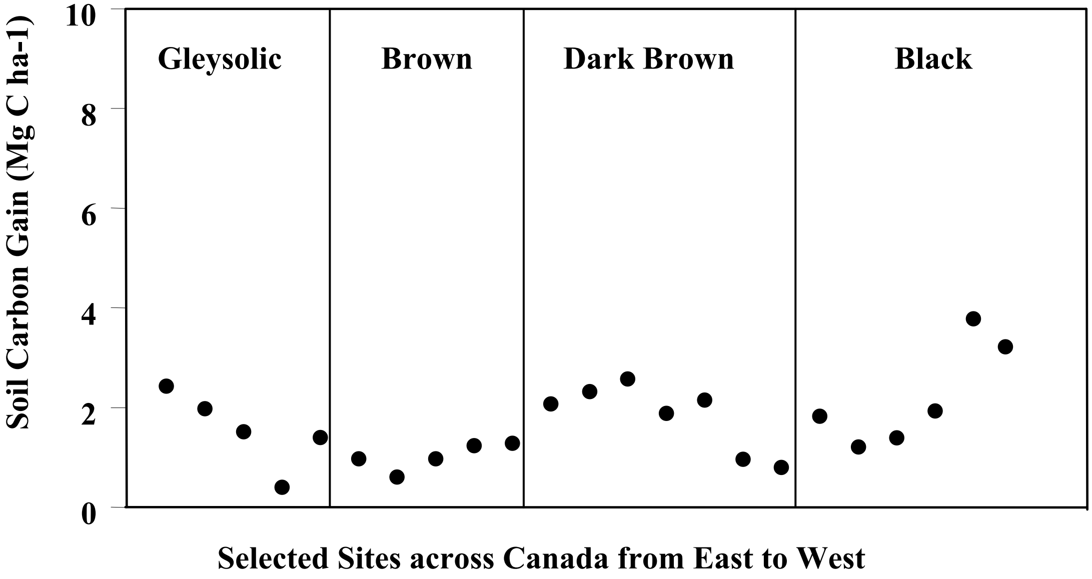

Figure 1. Soil C gained for four soil groups, in 10 years, as predicted by the Century model, due to conversion from conventional till to no-till.

to all soil groups. 5) It was assumed that about 2.8 Mha of the three Chernozemic soils could go from a wheat-wheat-fallow rotation to continuous wheat. The area of possible fallow reduction has been documented by Dumanski et al., (1999). Simplification of the crop rotations to achieve this fallow reduction was necessary to keep the scale of this project reasonable. 6) Wheat N-fertilizer application rates were simulated at 35, 50 and 70 kg ha^{-1} N for the Brown, Dark Brown and Black Chernozomic soil groups respectively. Normal N-fertilizer applications for corn were simulated at 140 kg ha^{-1} N for Gleysolic soils. To observe the influence of increased fertilizer amount on SOC change in the soil all N-fertilizer application rates were increased by 50%. 7) Approximately 15% of the total agricultural land in Canada is dedicated to perennial grass cover. An increase to 19% (i.e. equivalent to 1.7 Mha) was assumed. Forage was added as a continuous crop to the Brown, Dark Brown and Black Chernozemic soil groups. The total carbon gain on a given year was then subtracted from the same simulation without the introduction of perennial grass cover to calculate the SOC gain. These calculations were done on only a small number of polygons. A more extensive analysis can be found in Smith et al., (2001).

RESULTS AND DISCUSSION

Carbon gain due to conversion from conventional to no-till

To determine the SOC gained when converting conventional to no-tillage, no-tillage was introduced into the simulations in the year 1990. Carbon changes from 1990 to 2010 were compared against the base conventional tillage simulations. The Century model predicted that all soils gain SOC when converted from conventional to no-tillage (Figure 1). It was estimated that 23.1 Tg C could be sequestered in the four soil groups (Table 3). The potential exists for sequestering C in the other cultivated soils in Canada but no estimates are available at this time. Janzen et al. (1997) reported an average of 2.1 Mg ha^{-1} in experimental tests across Canada, ranging from 3 to 16 years. An older version of the Century (version 4.1) predicted values 40% lower. A more recent version of Century (April, 1999) predicted numbers that are much less variable than those observed but with a mean of 2.0 Mg ha^{-1} C over 10 years. Such results indicate that the model estimates agree well, on average, to what was observed across the country. Others, based on field observations, have suggested that the Century model might be underestimating the C sequestration in agricultural soils (McConkey et al. 1999). It is possible that the rate of the soil C gain, over relatively short periods, might be due to more favorable growing conditions as was demonstrated by Campbell et al., (2000).

Carbon gain due to reduction in the area under summer fallow

The Century model was used to compare SOC from the base wheat-wheat-fallow rotation to a continuous wheat rotation. The SOC gains were then multiplied by the expected area to be converted i.e. 1.7 Mha for the Brown and Dark Brown Chernozem and 1.1 Mha for the Black Chernozem soils resulting in a predicted gain of 9.1 Tg C (Table 3). This is equivalent to a gain of 0.46 Tg yr^{-1} C over a 20-year period.

Carbon gain from converting croplands to perennial grass cover

By increasing the area of perennial grass cover by 1.7 Mha the Century model predicted that 11.9 Tg C could be sequestered (Table 3). This is equivalent to 0.60 Tg C yr^{-1} over a 20-year period. The 0.5 Mha of grassland, which were established in 1989 as part of the Canadian Permanent Cover Program, primarily for soil conservation, fits very well under this scenario.

Table 3. Carbon gain as a function of management practices and soil groups over a 20-year period.

Soil Group	C Gain (Tg C) Tillage change	Reduction of summer fallow	Conversion to perennial grass cover	Fertilizer Effects
Br. Chern.	3.0		1.2	2.8
Dk. Br. Chern.	5.6	5.2	2.0	0.9
Blk. Chern.	13.3	3.9	8.7	0
Gleysolic	1.2			1.5
Western Canada	21.9			3.7
Eastern Canada	1.2			1.5
Canada	23.1	9.1	11.9	5.2

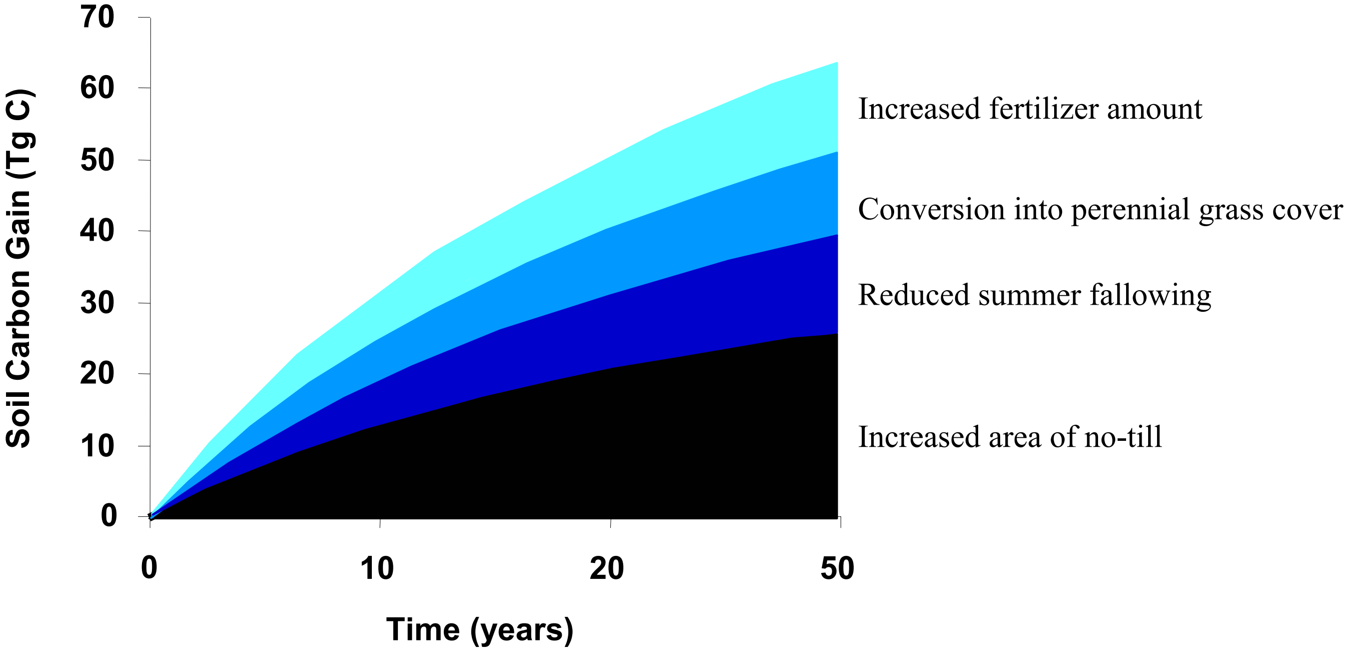

Figure 2. Predicted cumulative gain in soil organic carbon in agricultural soils in Canada as a result of increased area of no-till, reduced summer fallow, conversion into perennial grass cover and increased N-fertilizer amount.

Carbon gain due to increased crop production

Increase in SOC is closely linked to an increase in crop production. There are several ways to increase crop production, such as better crop varieties, improved water and nutrient management, etc. Better nutrient management will lead to increased crop production, increased crop residues returned to the soil and therefore increased soil organic matter. The magnitude of the increase in soil organic carbon is much larger in soils where C is inherently low than in ones where C is already high. Based on simulation runs with the Century model, a gain of 0 .26 Tg C y^{-1} or 5.2 Tg C is predicted over a 20-year period (Table 3). This can be achieved either through increased N fertilizer or increased fertilizer use efficiency. The latter would definitely be preferable because an increase in fertilizer would result in more N_2O emissions. Over a 20-year period, a 50% increase in N fertilizer would require Canada to produce 14.5 Tg N. Since 1.2 Tg C in the form of CO_2 is emitted for every Tg N of fertilizer produced, it means that we would release about 3 times more CO_2 in the production of the fertilizer than we would sequester in the soil due to increased crop production.

CONCLUDING REMARKS

Many benefits can be realized through sequestration of carbon in soils. It not only slows down the increase of greenhouse gases in the atmosphere but also improves soil health. The impact of the four measures discussed in this paper is summarized in Figure 2. These numbers amount to about 25 % of the maximum potential estimated by Bruce et al., (1999), but are roughly comparable to their estimate of C gain that might occur if there are no effective incentives for adoption of C-conserving practices. According to our estimates, the four measures could account for about 80% of the greenhouse gas emission reduction required by the primary agriculture sector in Canada to meet its part of the Kyoto commitment. There are many other possibilities to increase carbon sequestration. We have only examined four of the many mitigation measures possible, and have only dealt with about two thirds of the cropland. Furthermore, there may be additional synergistic benefits when the measures are applied together; for example, C gains from reducing tillage, eliminating fallow, and applying more fertilizer together could exceed that from the sum of the individual practices. However, as pointed out for the scenario involving increased N fertilizer, CO_2 is only one of the major agriculturally released greenhouse gases. C sequestration may require higher inputs of N fertilizer, which carries the risk of more CO_2 release from energy use and higher emissions of N_2O. Hence, the risk of N_2O production from management practices that favor carbon sequestration must be considered.

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REFERENCES

Angers, D.A., P. Voroney, M. Bolinder and J. Martel. 1993. Carbon sequestration by agricultural ecosystems in eastern Canada, a model approach. Green Plan, Greenhouse Gases Initiative report, Sainte-Foy, Quebec. 90 pp.

Bruce, J.P., M. Frome, E. Haites, H. Janzen, R. Lal. and K. Paustian. 1999. Carbon sequestration in soils. J. Soil & Water Cons. 54:382-389.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich and B. Blomert. 2000. Organic C accumulation in soil over 30 years in semiarid southwestern Saskatchewan – Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80:179-192.

Canadian Soil Survey Committee, Subcommittee on Soil Classification. 1978. The Canadian system of soil classification. Can. Dep. Agric. Publ. 1646. Supply and Services Canada, Ottawa, Ont.

Desjardins, R.L. and R. Riznek. 2000. Agricultural greenhouse gas budget. p. 133-142. In McRae, T., C.A.S. Smith and L.J. Gregorich (ed.) Environmental Sustainability of Canadian Agriculture: Report of the Agri-Environmental Indicator Project. Catalogue No. A22-201/2000E. Agriculture and Agri-Food Canada, Ottawa, Ont.

Dumanski, J., R.L. Desjardins, C. Tarnocai, C. Monreal, E. Gregorich, C.A. Campbell and V. Kirkwood. 1999. Possibilities for future carbon sequestration in Canadian agriculture in relation to land use change. J. of Climate 40:81-103.

IPCC. 1996. Climate change 1995: the science of climate change. Technical summary of the working group 1. Cambridge University Press, Cambridge.

Janzen, H.H., C.A. Campbell, E.G. Gregorich, and B.H. Ellert. 1997. Soil carbon dynamics in Canadian agroecosystems. Soil Carbon Dynamics in Canadian Agro-Ecosystems. p. 57-80. In: Lal, R. , John Kimble, Ron Follett and B.A. Stewart (ed.) Soil Processes and Carbon Cycles. CRC Press, Boca Raton.

Janzen, H.H., R.L. Desjardins, R. Asselin and B. Grace. (ed.) 1999. The Health of our Air: towards sustainable agriculture in Canada. Research Branch, Agriculture and Agri-Food Canada. Catalogue No. A53-1981/1998E.

Kulshreshtha, S.N., B. Junkins, R.L. Desjardins and J.C Giraldez. 2000. A systems approach to estimation of greenhouse gas emissions from the Canadian agriculture and agri-food sector. World Resource Review. 12:321-337.

McConkey, B.G., Liang, B.C. and C.A. Campbell. 1999. Estimating gains of soil carbon over a 15-year period due to changes in fallow frequency, tillage system, and fertilization practices for the Canadian Prairies (An Expert Opinion). Misc. Publication #379M0209, Swift Current Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food Canada.

Monreal, C.M.,R.P. Zentner and J.A. Robertson. 1995. The influence of management on soil loss and yield of wheat in a Brown Chernozem and Gray Luvisol. Can. J. Soil Sci., 75:567-574.

Parton, W.J., J. Persson and D.W. Anderson. 1982. Simulation of organic matter changes. In: Swedish soils Cultivation. Analysis of ecological systems: state-of-the-art in ecological modelling: proceedings, 24-28 May 1982, Colorado State Univ., Elsevier Scientific Pub Co. p.511-516.

Parton, W.J., D.S. Schimel, C.V. Cole and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51:1173-1179.

Parton, W.J., R.L. Sanford, P.A. Sanchez and J.W.B. Stewart. 1989. Modeling soil organic matter dynamic in tropical soils. *In:* D.C. Coleman, J.M. Oades, and G. Vehara, (ed). Dynamic of soil organic matter in tropical ecosystems.

Parton, W.J., J.M.O. Sherlock, D.S. Ojima, T.G. Gilmanor, R.J. Scholes, D.S. Schimel, T. Kirchner, J.C. Minaut, T Seastedt, E. Garcia Moya, A, Kamnalrut and J.I. Kinyamario. 1993. Observations and modeling of humus and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem. Cycle. 7:785-809.

Paustian, K., W.J. Parton and J. Persson. 1992. Modelling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil Sci. Soc. Am. J., 56:476-488.

Smith W.N., P. Rochette, C. Monreal, R.L. Desjardins, E. Pattey and A. Jaques. 1997. The rate of carbon change in agricultural soils in Canada at the Landscape level. Can. J. of Soil Sci. 77:219-229.

Smith, W.N., R.L. Desjardins and E. Pattey. 2000. The net flux of carbon from agricultural soils in Canada from 1970 – 2010. Global Change Biology. 6:557-568.

Smith, W.N., R.L. Desjardins and B. Grant. 2001. Estimated changes in soil carbon associated with agricultural practices in Canada. Can. J. of Soil Sci. (in press).