AGRI-ENVIRONMENTAL INDICATOR PROJECT

Agriculture and Agri-Food Canada

REPORT NO. 13

AGROECOSYSTEM GREENHOUSE GAS BALANCE INDICATOR: CARBON DIOXIDE COMPONENT

PROGRESS REPORT

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PREFACE

The Agri-Environmental Indicator (AEI) Project of Agriculture and Agri-Food Canada (AAFC) was initiated in 1993 in response to recommendations made by a number of agencies, organizations and special studies. The overall objective of the project is to develop and provide information to help integrate environmental considerations into decision-making processes at all levels of the agri-food sector.

The project aims to develop a core set of regionally-sensitive national indicators that build on and enhance the information base currently available on environmental conditions and trends related to primary agriculture in Canada. The Agroecosystem Greenhouse Gas Balance is one such indicator. Other indicators are being developed in relation to issues of soil quality, water quality, agroecosystem biodiversity, farm resource management and agricultural production efficiency.

Research results in the form of discussion papers, scientific articles and progress reports are released as they become available. A comprehensive report is planned in the period following the 1996 Census of Agriculture.

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1.0 Introduction

The atmospheric CO_2 concentration which contributes up to 65% to the global warming potential on a worldwide basis is increasing rapidly. It has increased from about 280 parts per million on a volume basis (ppmv) at the beginning of the industrial revolution to about 356 ppmv today (Schimel, 1995). Houghton (1995) estimated that changes in land-use from 1850 to 1990 resulted in cumulative emissions of 122 ± 40 Gt C which accounts for one half of the worldwide CO_2 increase.

Agriculture has the potential to act both as a source as well as a sink for several atmospheric greenhouse gases believed responsible for global warming potential. The three main greenhouse gases which can be regulated by agricultural activities are carbon dioxide, methane, and nitrous oxide. The potential for agriculture to sequester greenhouse gases comes mainly from the build-up of organic matter (carbon) in agricultural soils. Photosynthesis of agricultural crops is a major sink for atmospheric CO_2. The nonharvested plant biomass is returned to the soil and contributes to C sequestration. Sources of agricultural greenhouse gases include the oxidation of soil carbon, methane emissions from ruminant livestock and manure, and nitrous oxide emissions from nitrogen fertilizers, soils and animal wastes.

In order to better understand Canadian agriculture's contribution to greenhouse gas emissions, an indicator is being developed which aims at estimating the net agroecosystem greenhouse gas budget. This involves calculating emissions and/or uptake of each gas, converting these estimates into CO_2-equivalent units, and determining the difference between the emissions and uptake. This paper presents the results of work completed to date on the carbon dioxide balance component of the overall Agroecosystem Greenhouse Gas Balance indicator.

The sources and sinks of CO_2 in agroecosystems are reasonably well known, but the magnitude of the fluxes is more uncertain. From year to year little carbon is stored in above-ground biomass in agroecosystems. Furthermore, harvested carbon is rapidly respired by farm animals and humans. Thus the carbon balance in agroecosystems can be reduced to the CO_2 released from burning fossil fuel for farming activities and to the change in soil carbon. Statistics relative to fossil fuel use on farms is readily available (Statistics Canada, 1978-present). Data describing soil organic carbon (SOC) dynamics for agroecosystems are, however, unavailable for most landscapes of Canada. Furthermore, the accuracy of such data may be limited by spatial variability in the field and the precision of laboratory measurement techniques. As a result, not enough reliable data exist to sufficiently characterize soil carbon dynamics under the extensive variety of agricultural management and climatic conditions occurring across the country. For instance, the Black soil zone (Udic Borolls) comprises about 40% of the agricultural land in Canada, but there are only two ongoing long-term (>30 y) crop rotation studies in the zone (Campbell *et al.*, 1995b).

To construct a preliminary CO_2 balance for Canadian agroecosystems, two calculations were used. First, a modelling approach was used to simulate soil carbon change in agricultural soils, from which equivalent carbon dioxide emissions from soils were estimated. Second, CO_2 emissions were estimated from statistics on farm-use of fossil fuel. These two data sets were then combined to develop a net CO_2 emissions balance, as described in section 3.7.

Simulation models have synthesized knowledge of processes controlling SOC dynamics in grassland and cultivated soils (Parton *et al.*, 1987; McGill *et al.* 1981). The earliest of such models were simplistic in nature. The decomposition of SOC was described using a single first order differential equation. In later models differential equations representing transformation of various soil organic matter components were introduced which were further enhanced to describe soil organic matter along continuum of decomposability (Post III, 1992). Data for the turnover of SOC pools were obtained from studies using radiocarbon dating (Anderson and Paul, 1984; Campbell *et al.*, 1967). Validation attempts indicated that soil organic matter components were not satisfactory broken down into chemical and biological components such that decomposition rates for each component were uniform enough for modelling (Post III, 1992).

In some more recent modelling approaches, organic matter has been partitioned into well-defined components to which decomposition rates can be more readily applied. The Century model (Parton *et al.* 1993) and the Rothamsted turnover model (Jenkinson, 1990) are examples of such models. As input, the models require general soil, plant, and climatic data which is more readily available than some of the input for previous models.

Both the Century and the Rothamsted models are empirical in that many parameters were derived from long-term incubation and field studies. As indicated by Post III (1992) the main differences between these models are 1) the Rothamsted turnover model considers the passive carbon component to be inert whereas in Century small fluxes are received from the active and slow soil compartments and 2) in the Century model a reduction in soil organic matter results in lower levels of nitrogen hence less plant production and lower soil carbon. In the Rothamsted turnover model a change in organic matter level has no bearing on plant production thus it will generally show less carbon loss than Century.

The Century model has been extensively evaluated under contrasting soil, climatic and agricultural practices. It has been used in Eastern Canada (Angers *et al.*, 1993) Western Canada (Monreal *et al.*, 1995), the United States (Parton *et al*, 1987), in Northern Europe (Paustian *et al*, 1992; Parton *et al.*, 1982), and under tropical conditions (Parton *et al*, 1989).

The objective of this study was to estimate the rate of change of carbon content in agricultural soils in Canada at the landscape level and to discuss potential and limitations of using a model to calculate carbon change across contrasting soil, climate, and cropping conditions encountered in Canada.

2.0 Modelling Approach

Century, 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 savannas. It accounts for several agricultural management practices including planting, fertilizer application, tillage, grazing and organic matter addition. For our study, the versatility in a computer model is very important because of the extreme diversity in agricultural ecosystems across Canada. Century simulates above and below ground phytomass production as a function of soil temperature, available water, and nutrient availability. SOC is stabilized in slow cycling pools as a function of total amount of clay. Century is described in detail in Parton *et al.* (1993, 1989, and 1987).

2.1 Assumptions

Developing an approach to estimate carbon dynamics for a country with as much diversity in soil, climate and agricultural practices as Canada is a difficult task. Because of limitations in data availability, data quality, model performance, and labour resources several simplifications and assumptions had to be made:

1) Biomass burning, which has been decreasing for the last couple of decades, was not included.

2) It was assumed that a 15% rate of SLC polygon sampling was satisfactory to represent Canadian carbon dynamics.

3) Soil erosion was not considered in the Century runs. It was reasoned that soil erosion primarily moves organic matter laterally from one area of land to another within soil orders.

4) Manure additions were not considered for two reasons. First, the spatial variability of manure application is practically impossible to characterize on a landscape level. Second, it appeared that Century does not account properly for the labile nitrogen constituents in manures. For example, a run of continuous hay with manure resulted in an increase of SOC for a number of years, followed by a rapid decline, supposedly from the effect of nitrogen depletion on phytomass production.

5) Century has not been validated for some crops, including potatoes and pulse crops. These were not including in our simulations.

6) Runs were not done for minimum/conservation tillage. Campbell (1995a) and Kern and Johnson (1993) found little or no difference in carbon dynamics between conventional and minimum tillage.

7) We used the characteristics of the dominant soil of each selected polygon which represented at least 40% of the area of the polygon.

2.2 Stratification of Canadian Agricultural Soils for Analysis using the Century Model

Soil data for 1229 agriculturally designated polygons were obtained from the CanSIS Soil Landscapes of Canada (SLC) dominant characteristics files. This is the most extensive data base for agroecosystems in Canada. Table 1 shows the number of polygons within Provinces and soil orders.

A sample of 15% of the total number of agriculturally designated polygons in Canada was used to estimate carbon dynamics. Sampling of SLC polygons was stratified by major soil zones (Brown Chernozemic, Dark Brown Chernozemic, Black Chernozemic, Luvisols, etc.) and textural classes so that an equal percentage of the total area of each soil zone and textural class was sampled. Weighted sampling ensured representation of all prominent soil orders and soil textures within Canada.

The number of polygons sampled within a soil order was proportional to its fraction of the total Canadian agriculturally designated area. The number of SLC polygons sampled for Century analysis, by soil order, is shown in Table 1. A minimum of one polygon was sampled from each soil order. For Solonetzic soils, which represent 4% of the agricultural land in Canada, Century runs could not be carried out. Century does not describe well SOM dynamics in Solonetzic soils which have contributions of organic carbon and nitrogen from confined underlying aquifers.

Table 1 Designation of SLC polygons by province and soil development

Soil Order	British Columbia		Alberta		Saskatchewan		Manitoba		Ontario		Quebec		Atlantic		Canada		
	SLC	Area (kha)	SLC	Area (kha)	SLC	Area (kha)	SLC	Area (kha)	SLC	Area (kha)	SLC	Area (kha)	SLC	Area (kha)	SLC	Area (kha)	Polygons Sampled
Brown Chernozem	3	74	34	1862	121	4394									158	6330	24
Dark Brown Chernozem	8	77	43	2664	106	5536									157	8277	31
Black Chernozem	2	38	72	3595	121	6829	80	3860							275	15352	57
Dark Gray Chernozem or Dark Gray Luvisol	1	5	55	2232	56	1643	11	98							123	4874	18
Gray Brown Luvisol									125	3860					125	3860	14
Gray Luvisol	29	596	24	1230	20	542			9	98			2	59	84	2524	9
Brown Solonetzic			2	121	11	397									13	518	2
Dark Brown Solonetzic			1	68	7	1011									8	1078	4
Brunisolic Gray Luvisol	2	56											1	28	3	85	1
Black Solonetzic			16	926											16	926	3
Gray Solonetzic			2	58											2	589	1
Melanic Brunisolic	1	37							29	966	7	51			37	1053	4
Eutric Brunisolic	8	77													8	77	1
Sompric Brunisolic									1	8					1	8	1
Dystric Brunisolic	3	24									12	88			15	112	1
Humic Podzolic											1	10			1	10	1
Regosolic	5	25					2	95			22	154	14	30	43	305	1
Gleysolic	14	124	3	73	1	25	6	390	39	1510	52	1083	1	9	116	3213	12
Humo-Ferric Podzolic	7	107							1	21	12	162	22	502	42	793	3
Mesisol	1	14													1	14	1
Humisol	1	5													1	5	1
Total	85	1259	252	12829	443	20376	99	6369	204	6462	106	1549	40	628	1229	49472	190

The polygons within each soil order were further sorted by soil texture. The number of polygons to be sampled within a textural class was calculated as the fraction of the total area the texture represented within a soil order times the number of polygons sampled in the soil order. Samples within a textural class were chosen randomly. For example, for the Brown Chernozemic soil order, 11 polygons with a loam texture were chosen randomly from a population of 57.

2.3 Initialization of Century Input

The amount of phytomass produced and returned to soils are important parameters influencing SOM dynamics (Gregorich *et al.*, 1995). Under different climatic conditions the phytomass production component in Century requires modification (calibration) of some of the input parameters to produce acceptable crop yields. We calibrated crop yield and C-to-N ratios (30 cm depth) using a few SLC polygons in each soil order. Average crop parameters were then used for the remainder of the polygons in the soil order. An initial soil C-to-N ratio of approximately 10 was used for all soil orders except for Grey Luvisols where a value of 12.5 was applied based on unpublished data. The Land Potential Database (Kirkwood *et al.*, 1983) was used as a data source for calibrating crop yields. Estimates of historical yields as a percent of current yields were taken from Freyman *et al.* (1982). The main parameter used for calibration was "potential above-ground production for crops". Minimal calibration was also done using "root to shoot ratios" and "fraction of carbon in grain". Since these parameters influence partitioning of carbon into above- and below-ground pools, they were altered as little as possible. The calibration method produced excellent results for C-to-N ratios, however, crop yield as determined by Century were sometimes significantly different than yields in the Land Potential Database. Recalibration was required for some polygons within the same soil order.

Current carbon content to the 30 cm depth for each SLC polygon was estimated from the Soil Carbon Layer Database (Tarnocai, 1994). This database was accumulated by province over the last 20 years. It is the most comprehensive database on soil carbon for Canada. When possible, native carbon content was determined from native grassland/forest SLC polygons with soil properties similar to each respective polygon to be run. Otherwise, the native organic carbon content was estimated as follows;

$$\textit{Native carbon content} = \frac{\textit{Current carbon content}}{(1 - \textit{fraction of carbon lost since cultivation})}$$

where the carbon lost since cultivation was determined from various scientific studies (Dumanski *et al.*, 1995; Gregorich *et al.*, 1994; Monreal and Janzen, 1993; Anderson *et al.*, 1985).

2.4 Scheduling and Management Practices

Fertilizer scheduling and application rates used in Century for the Prairie provinces were primarily based on reports by Policy Branch, AAFC (1993-1995). The reports employed Agriculture Canada's Regional Agricultural Model (CRAM) and the Erosion Productivity Impact Calculator (EPIC) to predict erosion under various cropping systems in the Canadian Prairies. For this study the following exceptions to the fertilizer application rates in the CRAM/EPIC reports were made; 1) for the Brown Chernozems, no more than 30 kg ha^{-1} N was applied on wheat or barley, and 2) for the Black

Chernozems, no less than 70 kg ha^{-1} N was applied on wheat or barley. Fertilizer application rates for Eastern Canada were taken from Angers *et al.* (1993).

Information on crop rotations, planting, and harvesting schedules for the Prairie provinces was essentially based on CRAM/EPIC selection procedures, whereby, representative rotations were developed to summarize the complex set of cropping systems that occur in the Prairies. As an example, Table 2 shows that the crop rotations chosen for the province of Saskatchewan occurred in 9 CRAM regions and the selected rotations within any particular region consisted of an estimated 55 to 85% of the agriculture within the region. Rotations for the remainder of Canada, which account for 20% of the agricultural land were estimated from the following sources (Angers *et al*, 1993; The DPA Group Inc., 1988; Canada yearbooks and agricultural statistics; Hedlin and Kraft, 1981).

Table 2 Selected crop rotations for the province of Saskatchewan

CRAM Region	Rotations
1	WWF(40)*, WF(20), CWB(10), CWF(10)
2	WF(60), WWF(25)
3	WF(70), WWF(15)
4	WF(70), WWF(15)
5	CWWF(40), CWWB(15), WF(15)
6	WF(30), WWF(25), CWF(20)
7	CWF(30), WWF(10), WF(10), WBF(10)
8	CWWB(25), CWWF(20), BBHHH(20), CWB(10)
9	BBHHH(15), B(10), CWB(10), CWF(10)

* The number in brackets is the percent of the total agricultural area the rotation represents within a region.

W - Wheat
B - Barley
H - Hay
F - Fallow
C - Canola

Tillage practices for the Prairie provinces, including implements and scheduling, were also largely obtained from CRAM/EPIC. Further consultation, however, was carried out at research stations across Canada in an effort to better characterize the history of tillage practices. Table 3 shows an example of tillage scheduling used in Century. Carbon dynamics under conventional tillage practices were simulated for all polygons. Simulations were also carried out for no-tillage practices, providing the area of no-tillage in a polygon was greater than 5% of the polygons total agricultural area. Depending on the crop rotation, no-till blocks usually started in 1986, following conventional tillage from 1910 to 1985.

For all polygons, Century runs were carried out from 1910 to 1996. In order to better represent changing tillage and cropping practices the runs were broken into 4 or 5 time blocks. No-tillage was introduced in the 5th block (1985 to 1995). Reduction in summer fallow was reflected in Century analysis by exchanging some of the fallow rotations with more intensive rotations in latter blocks.

**Table 3 Tillage schedule for a wheat fallow rotation in the Canadian prairies.
C-till = conventional till N-till = no till**

	April	May	June	July	August	September	October
Spring wheat C-till	Cultivate Harrow	Fertilize 35N/10P Plant	Herbicide		Harvest grain	Cultivate	Herbicide
Summer fallow C-till		Cultivate		Cultivate	Cultivate		Tan disk Cultivate
Spring wheat N-till	Herbicide	Fertilize 35N/10P	Herbicide		Harvest grain		
Summer fallow N-till		Herbicide		Herbicide	Herbicide	Herbicide	

2.5 Calculations of the rate of SOC change

For each of 742 Century runs the rate of SOC change for the years 1980, 1985, and 1990 were determined by taking the slope of a 10 year regression centred on each particular year. For instance, the regression for the year 1990 was done over the time period from 1985 until 1995. Such a procedure was required to account for rotations which were several years long.

One to ten Century runs were carried out for each SLC polygon, depending on the number of crop rotations and tillage practices used in each. Calculation of the rate of carbon change for each polygon was done by weighting the results by tillage type and crop rotation as follows:

$$\Delta C = \sum_{t=1}^{T} F_t(\sum_{r=1}^{R} F_r C_r)$$

where ΔC = rate of carbon change for a polygon, T = number of tillage practices, R = number of crop rotations, F_t = fraction of area covered by tillage practice, F_r = fraction of area covered by crop rotation, and C_r = rate of change of carbon for the crop rotation.

A map showing the rate of carbon change for the year 1990 in Prairie soils, was generated by Kriging Century output for 120 SLC polygons. Lambert-meters were used as the coordinate system for the analysis. Each area on the map represents the average carbon loss from the polygons.

2.6 Sensitivity Analysis

A sensitivity analysis was carried out on seven prominent input parameters for the Century model in order to get an idea of how they affected the model output. First, a control run of Century was carried out for the year 1990 with no parameters changed, then, each of seven parameters was changed by plus and minus 20% while keeping the rest constant. The analysis was carried out for the three largest soil orders in Canada; the Brown, Dark Brown, and Black Chernozemic orders (Table 1).

It would have been useful, as well, to predict the uncertainty in Century estimates by stochastic means. Such an analysis would, however, require variances of input parameters. Such variances are not available from national landscape databases. For instance, a database of soil characteristics for Canada, the Canada Soil Information System (CANsis), consists of densely measured data, sparsely measured data and estimated data, each having different ranges of variance. This is, however, the best soil data available at the landscape level in Canada.

3.0 Results and Discussion

3.1 Rate of soil organic matter change in Canada

The average amount of SOC in the Chernozemic soil order in Canada is estimated to be 125 000 kg ha^{-1} (Tarnocai, 1994). Tabatbai and Bremner (1970) as well as Froelich (1980), found at best a 1% error in determining total organic carbon content in soils using dry combustion and acid digestion. Based on these values total SOC in Chernozemic soils could be measured in the laboratory with an accuracy of ± 1250 kg ha^{-1}. In this study the overall rate of carbon loss from agricultural soils in Canada for the year 1990 was estimated to be 39.1 kg ha^{-1} y^{-1} (Table 4). This implies a net loss of 1.93 Mt of carbon, equivalent to 7.09 Mt of CO_2 for agricultural soils in Canada.
Considering the magnitude of the carbon storage term in agricultural soils in Canada and the capability to measure change in this storage term, such yearly rates of carbon loss are not measurable analytically and are usually considered to be at near equilibrium. The loss does, however, represent 69% of the annual amount of CO_2 released by the burning of fossil fuel used on farms in Canada (10.4 Mt CO_2) (Liu, 1995). In 1980 and 1985 the rate of SOC loss in agricultural soils in Canada was higher than in 1990. The estimated reduction in the rate of carbon loss was small between 1980 and 1985 (1.8 kg ha^{-1}), but larger between 1985 and 1990 (9.1 kg ha^{-1}). This is partly due to the influence of no-till practices which were introduced to some areas in the mid 1980's. The reduction in summerfallow (more intensive cropping systems) in the latter time blocks used in Century also resulted in less carbon loss in latter years.

A frequency distribution of the rate of SOC change for all sampled polygons for the years 1980 and 1990 shows that there was a wide range in simulated SOC change across Canada (Fig. 1). The frequency distribution of SOC change for the year 1985, which is not shown, was similar to that of the year 1980. SOC loss between -10 and -40 kg ha^{-1} y^{-1} occurred most frequently. Much of the SOC change in this range can be attributed to losses from polygons in the Brown Chernozemic soil. Century simulations indicated that carbon sequestration occurred in approximately 14 and 20% of the total number of polygons sampled in Canada for the years 1980 and 1990, respectively.

The rate of carbon change for the year 1990 in Prairie soils is shown in Fig. 2. Each shaded area represents the average carbon loss from the polygons that occur in that area. Estimates in certain locations such as in Northern Manitoba are not as reliable because very few sampled polygons were used to characterize these areas. A definite pattern was obtained, showing more carbon loss in central Alberta and Manitoba. The main reason for this was that the native carbon content in these areas was higher than in most other areas of the map, even within the same soil order. In Black Chernozemic soils, to the 30 cm depth, the average carbon content was calculated to be 132060, 115520, and 99370 kgC ha^{-1} y^{-1} in Alberta, Manitoba, and Saskatchewan, respectively.

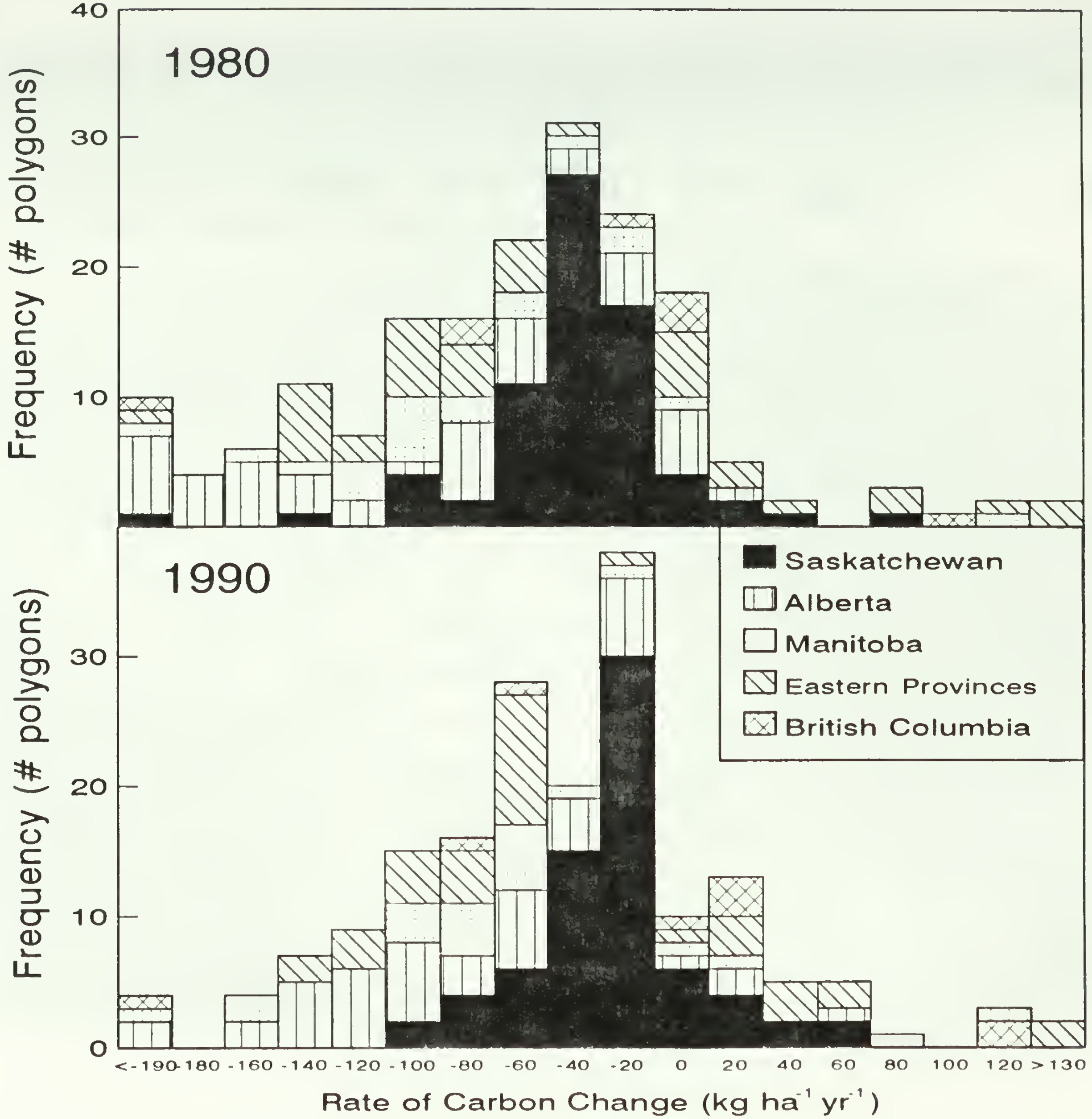

Figure 1 Frequency distribution of the rate of carbon change for the years 1980 and 1990 from all polygons sampled in Canada (total size = 180 polygons)

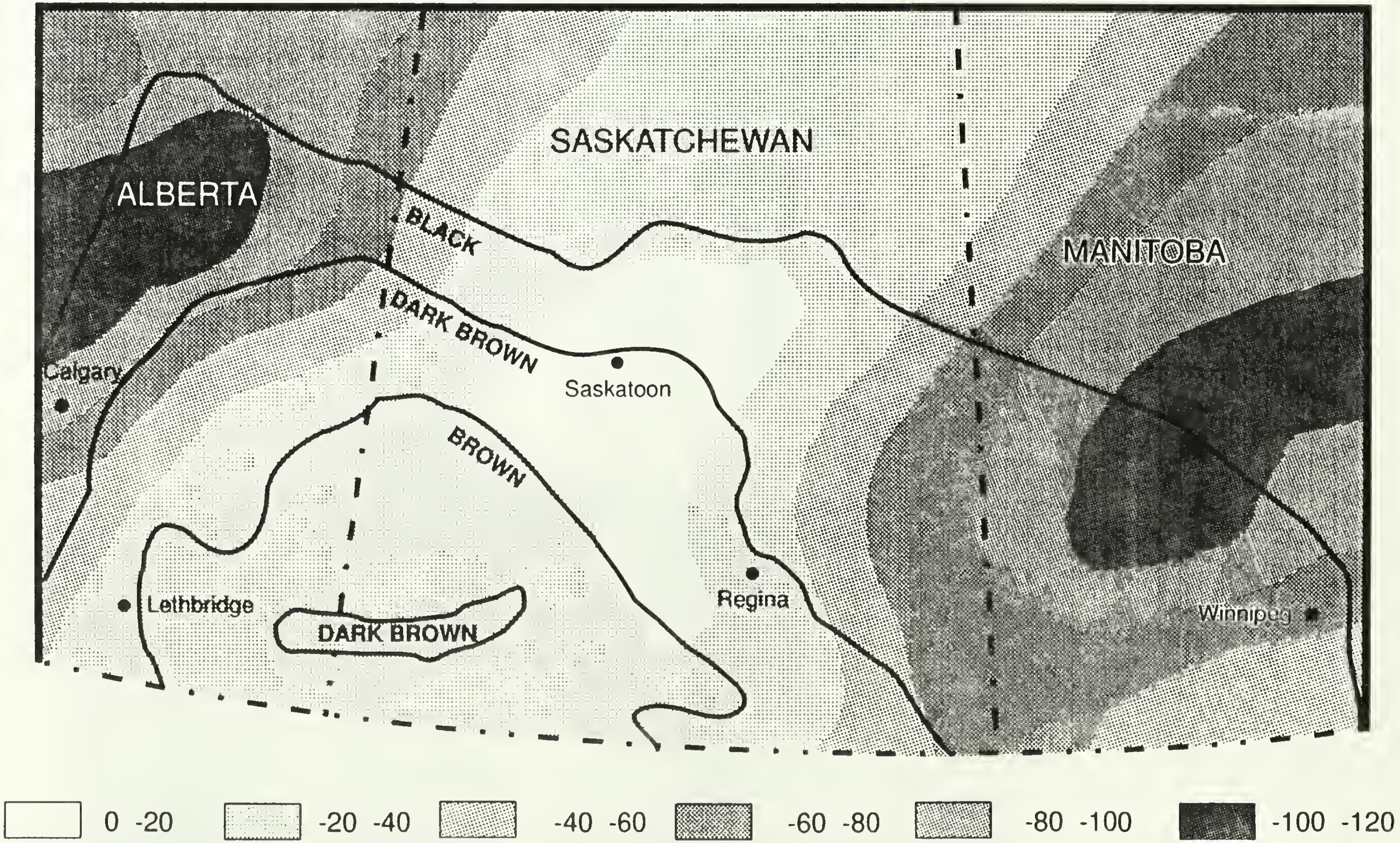

Figure 2 Rate of carbon change (Kg ha^{-1}) in prairie soils for the year 1990

Table 4 Rate of SOC change for the 0-30 cm depth in agricultural soils of Canada

Region	1980		1985		1990		Area		Carbon loss from 1910 to 1990 (%)
	Rate	Total	Rate	Total	Rate	Total			
	kg ha^{-1} y^{-1}	Mt y^{-1}	kg ha^{-1} y^{-1}	Mt y^{-1}	kg ha^{-1} y^{-1}	Mt y^{-1}	Sampled (kha)	Total (kha)	
Atlantic	-12.5	-0.008	-9.6	-0.006	+4.26	+0.003	182	628	3.0
Quebec	-40.2	-0.062	-37.2	-0.058	-34.5	-0.054	274	1549	17.9
Ontario	-6.6	-0.043	-5.7	-0.037	-4.12	-0.027	1071	6462	12.5
Manitoba	-76.7	-0.488	-73.2	-0.466	-66.1	-0.421	1161	6369	25.6
Saskatchewan	-39.3	-0.800	-36.5	-0.744	-22.5	-0.458	3419	20376	20.6
Alberta	-84.0	-1.080	-79.9	-1.030	-74.5	-0.956	2189	12829	27.9
British Columbia	-33.7	-0.042	-31.1	-0.039	-16.1	-0.020	100	1259	13.3
Canada	-51.0	-2.523	-48.2	-2.380	-39.1	-1.933	8397	49427	21.7

3.2 Rate of soil organic matter change by province

The total carbon losses from Prairie soils comprised greater than 90% of the carbon loss in Canada. This is due to the fact that 80% of the agricultural land in Canada is in the Prairies (Table 1) and that most of this land has a high natural carbon content. Also, the change from native to agricultural land occurred later in the west than in the east. Century simulations indicated that Alberta and Manitoba had the highest rate of carbon loss (Table 4). Based on estimates using the nitrogen budget, Curtin *et al.* (1993) determined that the annual loss of carbon from Saskatchewan may be about 100 kg ha^{-1} y^{-1}. We estimated that the net losses of SOC from Saskatchewan in 1990 was 22.5 kg ha^{-1} y^{-1}. Such a rate of loss is undetectable with the available technology. One reason for the discrepancy may be that we are looking at net oxidative losses of CO_2 and not losses of carbon in eroded soil. We make the assumption that the eroded soil moves laterally to other agricultural land or to ditches and nonagricultural land. When eroded soil moves to ditches and nonagricultural land, all the carbon in the soil is lost from the agricultural land, however, it is not all transformed into CO_2. In lack of better data, the rate of oxidative loss of CO_2 from the eroded agricultural soil is assumed to be the same as that from agricultural land.

A lower rate of loss in Saskatchewan than in Alberta and Manitoba does not necessarily indicate better soil management practices. In some instances, SOC was lost rapidly shortly after cultivation began, resulting in SOC steady state within less than a few decades, thus little or no carbon was lost in later years. Such soils may be more responsive to carbon sequestration on introduction of better management practices (ie. reduction in fallow, increased no-till operations).

Carbon loss in the eastern provinces were generally less than in the west. Most of the land in the east has been in cultivation much longer and as a result the soils tend to be closer to equilibrium. Land in agricultural regions in Quebec showed a more rapid carbon loss than Ontario soils. According to the carbon database in CANsis the top 30 cm of agricultural soils in Quebec is on average approximately 60% higher in carbon content than in Ontario (Soil Carbon Data Base Working Group, 1993). This is because of; 1) more hay is grown in Quebec, 2) poorer drainage in Quebec until subsurface drainage was added 15 to 30 years ago, and 3) a difference in the original soil parent material (Jean-Marc Cossette, personal communication).

3.3 Rate of soil organic matter change within soil orders

The estimated rates of SOC loss in the Dark Gray Chernozemic/Luvisolic and Black Chernozemic orders for 1980, 1985, and 1990 was from 2 to 4 times higher than in any other soil order (Table 5). The relative carbon lost from 1910 to 1990 was, however, similar to other Chernozemic soils. This was because the Dark Gray Chernozemic/Luvisolic and Black Chernozemic soil orders had very high native carbon contents. McGill *et al.* (1988) estimated that from 15-30% of the native carbon in Prairie soils was lost since cultivation. Similarly, Anderson (1995) and Monreal and Janzen (1993) found that approximately 17% of the carbon was lost from Chernozemic soils. Predictions by Century indicated that an average of about 24% of the carbon has been lost via oxidation since cultivation.

Table 5 Predicted SOC change in the 0-30 cm depth by soil order in Canada

Soil Order	1980		1985		1990		Area		Carbon loss from 1910 to 1990 (%)
	kg ha^{-1} y^{-1}	Mt y^{-1}	kg ha^{-1} y^{-1}	Mt y^{-1}	kg ha^{-1} y^{-1}	Mt y^{-1}	Sampled (kha)	Total (kha)	
Brown Chernozemic	-26.9	-0.170	-27.4	-0.174	-22.6	-0.143	830.2	6330	18.1
Dark Brown Chernozemic	-38.4	-0.318	-35.6	-0.295	-15.6	-0.129	2160.4	8277	22.4
Black Chernozemic	-94.8	-1.456	-89.1	-1.368	-84.1	-1.291	2665.6	15352	26.8
Dark Gray Chern./Luv.	-77.5	-0.378	-69.7	-0.340	-59.6	-0.288	738.3	4874	27.3
Gray Brown Luvisolic	-8.7	-0.033	-9.3	-0.036	-10.1	-0.051	457.8	3860	14.3
Gray Luvisolic	-22.3	-0.056	-25.5	-0.064	-20.1	-0.051	452.9	2524	10.4
Gleysolic	-9.7	-0.031	-8.6	-0.028	-1.7	-0.006	820.1	3213	12.3
Other	+4.0	+0.020	+5.3	+0.027	+8.1	0.041	471.3	5042	10.0

The overall summation of the polygons within each soil order usually resulted in a loss of SOC, however, it should be noted that organic carbon was sometimes sequestered for certain crop rotations and soil types. Fig. 3A shows that for identical crop rotations, more carbon will be sequestered in a fine textured soil. In this simulation, a wheat-fallow (WF) crop rotation (1910-1929) is followed by a continuous barley rotation (1930-1995) for a clay and a sandy loam soil. By the year 1990, more SOC remained in the clay than in the sandy loam soil. Fig.3B shows an example of the impact of different crop rotations on carbon storage, for the same soil, and under identical climatic conditions. By the year 1990, there was a net loss of SOC under WF and a slight net gain under wheat-wheat-fallow (WWF) crop rotation. Century runs show more carbon loss from soil for fallow rotations than for any other rotation. This finding supports the conclusion by McGill *et al.* (1988) that fallowing is a practice which contributes significantly to the decline in soil carbon in Prairie soils.

The effect that conventional and no-till management practices may have on carbon storage in Brown and Black Chernozemic soils is shown in Figure 4. Use of no-till reduced SOC loss in the Brown Chernozemic soil and induced a net gain in the Black Chernozemic soil. As expected, no-till management results in less carbon loss from soil than conventional-till systems. The effect of tillage on carbon storage is variable depending on environmental factors such as soil type, climate, and management.

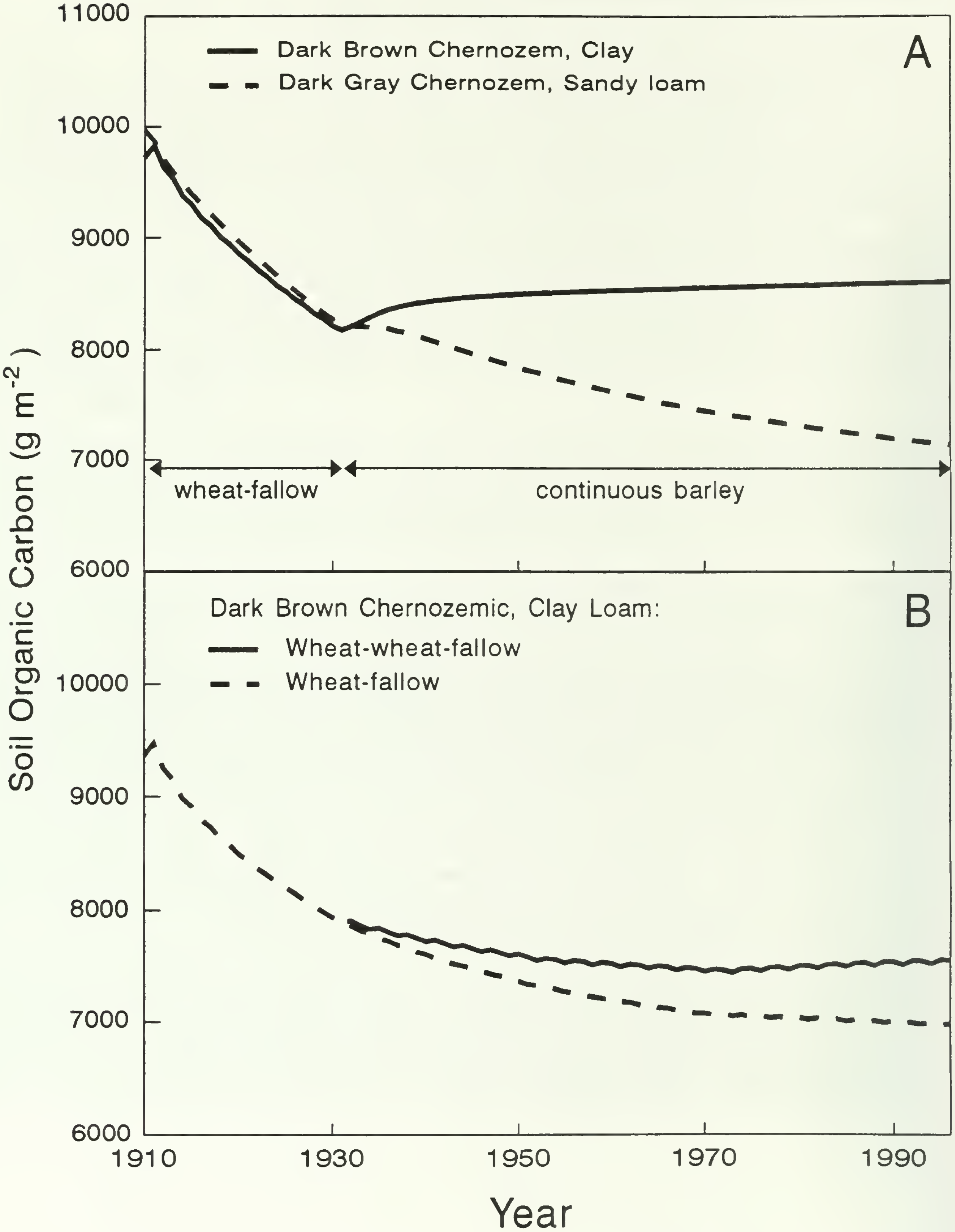

Figure 3 Century predictions for different soils and crop rotations

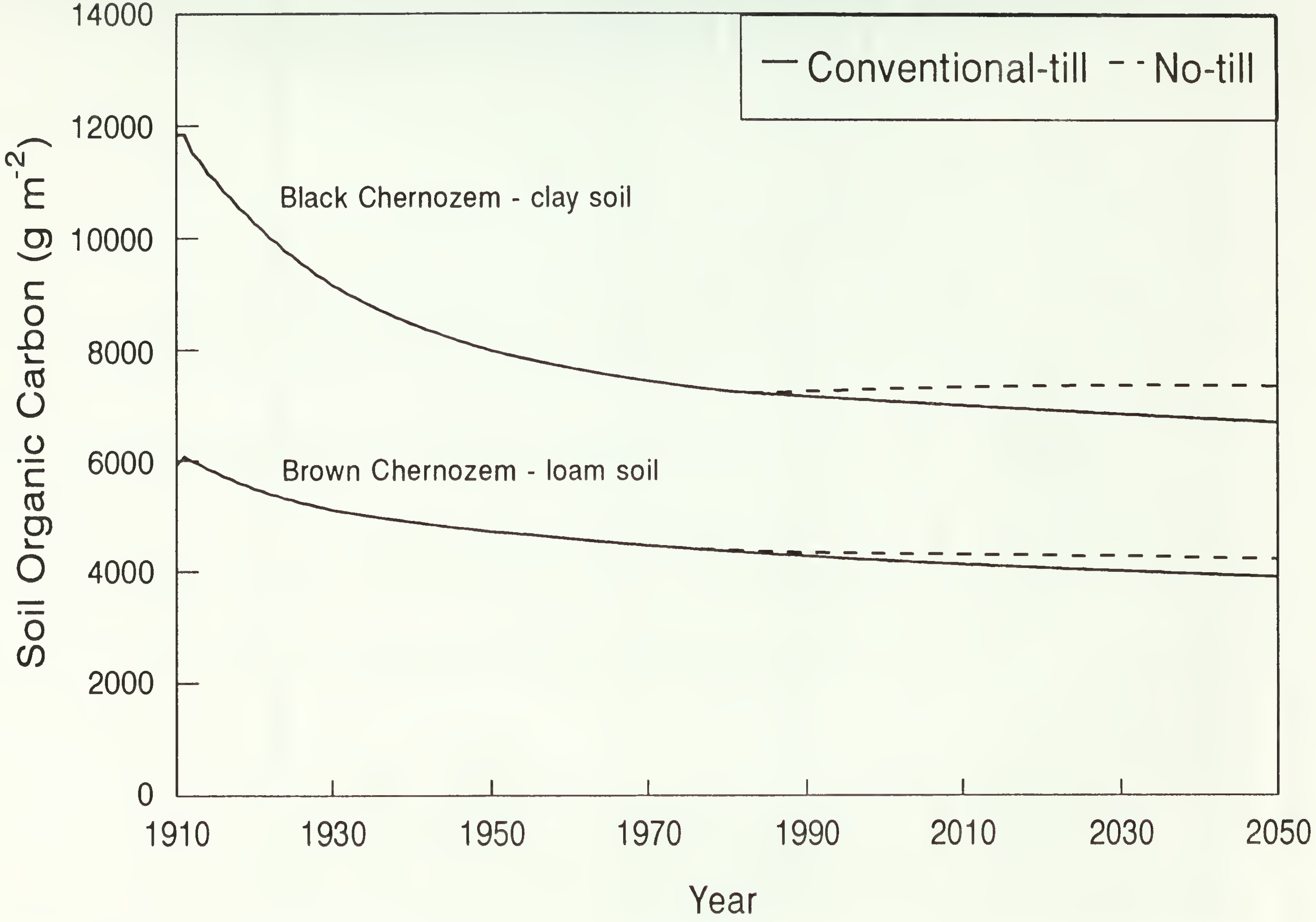

Figure 4 Century predictions under conventional and no-till management

3.4 Influence of texture

The rate of change of carbon in various soil textures is shown in Table 6. The rates of loss were higher in the coarse textured than the fine textured soils. Coarse textured soils are more aerated thus provide a better environment for organic matter decomposition by microbial activity. Also, in fine textured soils, there is a physical protection of organic matter to microbial oxidation by clay aggregates. The amount of carbon lost from 1910 to 1990 was greater than 20% for all textures coarser than the loam soil. The 13 different textures were grouped into fine, medium and coarse texture classes. The loams and silty loams were grouped into a medium textural class. All soils of finer texture than the silty loams were grouped into the fine textural class and all textures of coarser texture than the loams were grouped into a coarse textural class. The three textural groups showed marked differences in the rate of carbon loss from soils.

Table 6 Rate of change of SOC by soil texture

Texture	1980 kg ha^{-1} y^{-1}	1985 kg ha^{-1} y^{-1}	1990 kg ha^{-1} y^{-1}	Number of Polygons	Carbon loss from 1910 to 1990 (%)
Heavy clay	-35.0	-31.1	-6.07	6	14.6
Clay	-11.7	-9.7	-7.91	15	16.3
Silty Clay	-2.0	-1.9	+1.59	1	5.5
Silty clay loam	-20.2	-17.5	-2.8	8	13.8
Clay loam	-65.7	-60.6	-52.5	20	17.5
Silty loam	-30.7	-32.4	-31.3	21	14.7
Loam	-63.9	-60.5	-53.3	86	23.7
Very fine sandy loam	-33.5	-30.7	-25.6	1	24.0
Fine sandy loam	-89.8	-81.9	-53.9	5	29.8
Sandy loam	-101.3	-93.6	-85.5	13	32.0
Loamy fine sand	-195.2	-185.4	-108.8	1	32.6
loamy sand	-89.4	-83.8	-84.0	2	30.7
Fine sand	-180.2	-182.5	-142.0	1	34.3
Fine	-29.9	-26.7	-13.3	50	15.9
Medium	-59.1	-56.4	-50.1	107	22.2
Coarse	-103.0	-96.0	-81.4	23	31.0

3.5 Sensitivity analysis of Century output for selected parameters

The sensitivity analysis results in Table 7 are reported as the deviation in carbon change from the control run. For instance, in the Brown Chernozem a plus 20% change in the native carbon content results in a 12.5 kgC ha^{-1} reduction in the rate of carbon change. This means that 35.1 kgC ha^{-1}, instead of 22.6 kgC ha^{-1} would be lost in the year 1990. The rank in descending order of seven input variables is shown in Table 8. Rainfall, when varied by -20% had the largest effect on model output. This is not surprising considering that the Brown Chernozem soil orders have very little rainfall. Temperature had the largest effect on model output when parameters were varied by +20%. It is interesting that for both positive and negative changes in temperature there was a decrease in the amount of carbon lost for the year 1990. This indicates that in Century temperature does not have a linear effect on carbon change in soil. Several rates may change simultaneously as temperature changes. For instance, the addition of plant biomass to soil may increase, but the rate of microbial decomposition of organic matter may also increase. Nitrogen fertilizer application and native carbon content were the next two most sensitive parameters.

In the Dark Brown Chernozem, the rate of carbon change as predicted by the Century model was most sensitive to temperature. In the Black Chernozem, carbon change was most sensitive to the level of native carbon. In all three soil orders temperature and native carbon were generally the most important parameters whereas soil carbon change was usually not very sensitive to clay content. The sensitivity of the model output to a change in a parameter varied tremendously and most often had nonlinear influences on carbon dynamics. It can be concluded that the effect that changes in input parameters have on Century output is highly variable, depending on specific run conditions. For all three soil orders, any change of 20% in a parameter resulted in a change in carbon content of less than 50 kgC ha^{-1} y^{-1}. It is encouraging that the parameter with the greatest influence is temperature for which we have a relatively high confidence. On the other hand, soil native carbon content, which is highly variable, also had a large effect on the rate of change of soil carbon.

Table 7 The effects of changing input variables on the rate of SOC change in Prairie soils

	Brown Chernozem, rate of carbon change for control = -22.6 kgC ha^{-1} y^{-1}			Dark Brown Chernozem, rate of carbon change for control = -30.7 kg C ha^{-1} y^{-1}			Black Chernozem, rate of carbon change for control = -88.4 kgC ha^{-1} y^{-1}		
Model Parameter	Parameter in control run	Deviation in Rate of carbon change (kgC ha^{-1} y^{-1})		Parameter in control run	Deviation in Rate of carbon change (kgC ha^{-1} y^{-1})		Parameter in control run	Deviation in Rate of carbon change (kgC ha^{-1} y^{-1})	
		+20 %	-20 %		+20 %	-20 %		+20 %	-20 %
Bulk Density	1.40 g cm^{3}	+0.0	+0.0	1.30 g cm^{3}	-24.9	-9.7	1.30 g cm^{-3}	-20.8	+11.1
Clay	13 %	+0.5	-0.6	34 %	+4.3	-4.3	34 %	-0.4	-1.9
Native Carbon	55050 kgC ha^{-1}	-12.5	+12.1	93650 kgC ha^{-1}	-38.6	-16.6	114700 kg ha^{-1}	-40.7	+41.6
Fertilizer-N	30 kg ha^{-1}	+21.2	-22.1	35 kg ha^{-1}	-0.9	-28.1	70 kg ha^{-1}	-1.0	+1.7
PRDX[1]	350 kgC ha^{-1}	-9.6	+5.9	350 kgC ha^{-1}	-28.7	-43.3	350 kgC ha^{-1}	+34.1	-32.4
Rain[2]	34.6	-4.6	+48.4	35.7 cm	+0.2	-19.1	43.2 cm	+0.6	-5.2
Temperature[3]	3.8 °C	+25.6	+1.2	3.8 °C	-57.2	-47.1	2.5 °C	+40.2	+4.9

1 potential above ground crop growth
2 total yearly precipitation
3 average annual temperature

Table 8 Rank in descending order of seven input variables used in Century

Brown Chernozem		Dark Brown Chernozem		Black Chernozem	
+20 %	-20 %	+20 %	-20 %	+20 %	-20 %
Temperature	Rain	Temperature	Temperature	Carbon	Carbon
Fertilizer-N	Fertilizer-N	Carbon	PRDX	Temperature	PRDX
Carbon	Carbon	PRDX	Fertilizer-N	PRDX	Bulk Density
PRDX	PRDX	Bulk Density	Rain	Bulk Density	Rain
Rain	Temperature	Clay	Carbon	Fertilizer-N	Temperature
Clay	Clay	Fertilizer-N	BD	Rain	Clay
Bulk Density	Bulk Density	Rain	Clay	Clay	Fertilizer-N

3.6 Estimated carbon dioxide emissions from farm fossil fuel use

Tables 9 to 12 show fossil fuel consumption and resulting CO_2 emissions by province for the years 1986 and 1991. The largest emissions of CO_2 were in Alberta, Saskatchewan, and Ontario, with most of the emissions coming from the burning of motor gasoline and diesel oil. CO_2 emission factors for the fuels was taken from Jaques (1992).

Table 9 Fossil fuel consumption in the agricultural sector in 1986

Province	Natural gas	Motor Gasoline	Kerosene & stove oil	Diesel oil	Light fuel oil	Heavy fuel oil	Total
	(TJ y^{-1})						
Newfoundland	0	132	23	79	307	0	541
PEI	0	300	40	242	276	0	858
Nova Scotia	0	371	119	734	1304	30	2558
New Brunswick	0	840	76	499	1008	0	2423
Quebec	0	3586	203	4674	2185	550	11198
Ontario	6630	7323	225	6140	3137	259	23714
Manitoba	0	5650	17	5320	513	0	11500
Saskatchewan	2203	14890	44	16099	548	0	33784
Alberta	7725	16084	18	18373	140	0	42340
British Columbia	1741	2374	520	3005	459	0	8099
Yukon & NWT	0	78	5	27	26	0	136
Total	18299	51628	1290	55192	9903	839	137151

Table 10 CO_2 emission from fossil fuel consumption in the agricultural sector in 1986

Province	Natural gas	Motor Gasoline	Kerosene & stove oil	Diesel oil	Light fuel oil	Heavy fuel oil	Total
	(kt CO_2 y^{-1})						
Newfoundland	0	9	2	6	22	0	39
PEI	0	20	3	17	20	0	60
Nova Scotia	0	25	8	52	95	2	183
New Brunswick	0	57	5	35	74	0	171
Quebec	0	244	14	330	160	41	788
Ontario	329	498	15	434	229	19	1525
Manitoba	0	384	1	376	38	0	799
Saskatchewan	109	1012	3	1138	40	0	2303
Alberta	384	1093	1	1299	10	0	2787
British Columbia	86	161	35	212	34	0	529
Yukon & NWT	0	5	0	2	2	0	9
Total	909	3510	87	3902	724	62	9194

Table 11 Fossil fuel consumption in the agricultural sector in 1991

Province	Natural gas	Motor Gasoline	Kerosene & stove oil	Diesel oil	Light fuel oil	Heavy fuel oil	Total
	(TJ y^{-1})						
Newfoundland	0	54	89	54	443	0	640
PEI	0	422	42	460	228	0	1152
Nova Scotia	0	317	252	449	2163	134	3315
New Brunswick	0	444	67	463	807	0	1781
Quebec	216	3592	264	5362	3689	234	13357
Ontario	8619	8135	249	10320	4247	205	31775
Manitoba	145	4425	42	8648	396	0	13656
Saskatchewan	3912	14899	46	21165	512	0	40534
Alberta	7183	14561	42	17771	137	0	39694
British Columbia	3125	1528	597	2474	1875	0	9599
Yukon & NWT	0	10	9	10	164	0	193
Total	23200	48387	1699	67176	14661	573	155696

Table 12 CO_2 emission from fossil fuel consumption in the agricultural sector in 1991

Province	Natural gas	Motor Gasoline	Kerosene & stove oil	Diesel oil	Light fuel oil	Heavy fuel oil	Total
	(kt CO_2 y^{-1})						
Newfoundland	0	4	6	4	32	0	46
PEI	0	29	3	33	17	0	81
Nova Scotia	0	22	17	32	158	10	238
New Brunswick	0	30	5	33	59	0	126
Quebec	11	244	18	379	270	17	939
Ontario	428	553	17	730	310	15	2053
Manitoba	7	301	3	611	29	0	951
Saskatchewan	194	1013	3	1496	37	0	2744
Alberta	357	990	3	1256	10	0	2616
British Columbia	155	104	40	175	137	0	611
Yukon & NWT	0	1	1	1	12	0	14
Total	1153	3289	115	4749	1072	42	10420

3.7 Estimated net carbon dioxide balance for Canadian agroecosystems

An estimate of the total CO_2 emissions occurring in Canada in the years 1985 and 1990 are shown in Table 13. The Century estimates indicated that there was considerably less CO_2 emissions from agricultural soils in 1990 than in 1985. There was, however, more emissions from burning fossil fuels in 1990 than in 1985. As a result the total overall emissions for 1985 and 1990 were very similar. In 1985 the emissions of CO_2 from agricultural soils accounted for 49% of the total emissions whereas it accounted for only 41% in 1990. The increased emissions from fossil fuels was most likely due to an increase in more intensively farmed land.

Table 13 Estimated net carbon dioxide balance for Canadian agroecosystems - 1985 and 1990

Region	CO_2 emission balance for 1985 (kt CO_2 y^{-1})			CO_2 emission balance for 1990 (kt CO_2 y^{-1})		
	Soils	Fossil fuels	Sum	Soils	Fossil Fuels	Sum
Atlantic	22	453	475	-11	491	480
Quebec	213	788	1001	198	939	1137
Ontario	136	1525	1661	99	2053	2152
Manitoba	1709	799	2508	1544	951	2495
Saskatchewan	2728	2303	5031	1679	2744	4423
Alberta	3777	2787	6564	3505	2616	6121
British Columbia	143	529	672	73	611	684
Total	8728	9184	17912	7087	10405	17492

4.0 Summary and Conclusions

The accurate estimation of the rate of carbon change in agricultural soils in Canada is a difficult undertaking. The models available to predict soil carbon dynamics are empirical and the use of a single model across the contrasting soil, climate and cropping conditions encountered in Canada undoubtedly results in uncertainty. Also, the quality of data in national databases varies for different parameters and localities. In the future, as the databases improve, it should be possible to provide confidence limits to estimates. Despite these shortcomings, the present study constitutes a reasonable objective assessment of the rate of change of carbon in agricultural soil in Canada.

The overall net rate of carbon loss from agricultural soils in Canada for the year 1990 was 39.1 kg ha^{-1} y^{-1}. This implies that 1.93 Mt of carbon or 7.08 Mt of CO_2 was lost from Canadian soils. The loss represents 69% of the annual amount of CO_2 released by the burning of fossil fuel used on farms in Canada. Overall losses of carbon were 11.9 and 9.1 kg ha^{-1} y^{-1} greater in the years 1980 and 1985, respectively, than in the year 1990. This was primarily due to the effects of introduction of no-tillage and less summer fallow in the mid 1980's. Since the amount of no-till agricultural land has further increased since 1990, we may expect to see further reduction in carbon loss in 1995.

The carbon loss in the Prairies accounted for more than 90% of the carbon loss in agricultural soils in Canada. Alberta and Manitoba had the highest rate of carbon loss in 1990 at 74.5 and 66.1 kg ha^{-1} y^{-1}, respectively. In the Eastern provinces (Atlantic, Quebec, and Ontario) the average provincial rate of carbon loss did not exceed 35 kg ha^{-1} y^{-1}.

Higher carbon losses were typically found in soil orders with greater native carbon contents. Estimated loss for sampled polygons in the two soil orders with the highest native carbon content, the Brown Chernozemic and Dark Gray Chernozemic/Dark Gray Luvisolic orders was more than double that of any other soil order. Within a soil order, more losses were found in soils with coarser texture.

The sensitivity of the rate of carbon change in soil, as predicted by the Century model, to some of the major input parameters was highly variable, being dependent on site specifics. Temperature and native carbon content were the two parameters which generally affected Century output the most. A change of plus or minus 20% in these parameters resulted in a change in soil carbon content of less than 50 kgC ha^{-1} y^{-1}.

The total emissions of CO_2, including emissions from agricultural soils and burning of fossil fuels, was estimated to be 17.91 mt CO_2 y^{-1} for 1985 and 17.49 mt CO_2 y^{-1} for the year 1990. In 1985 the emissions of CO_2 from agricultural soils accounted for 49% of the total emissions whereas it accounted for 41% in 1990.

5.0 Further Research Work

Changes in land use have been identified as a major contribution to the increase in greenhouse gas emissions. So far we have demonstrated that for different cultural practices, soils can either be a sink or source of CO_2. The Century model, whose primary data driver requirements are average monthly climate (min & max temperature, precipitation), soil texture and management characterization, has been particularly useful to quantify the change in organic carbon in soils over the last 85 years. In the future, we plan to use Century to forecast level of carbon in agricultural soils associated with changes in management practices such as a shift towards: more forage crops, more intensive use of fertilizers, less summerfallowing and/or a reduction in tillage. Micrometeorological techniques can be used to verify model predictions for all these scenarios but because of the temporal variability of soil processes measurements must be collected through several annual cycles.

Changing a cultural practice in order to increase carbon sequestration in soils can also affect the fluxes of other greenhouse gases such as CH_4 and N_2O. Because of the considerably higher global warming potential of these gases as compared to CO_2 the interrelationship between the sources and sink of these gases is very important. For example, there are a whole series of measures, which while they increase carbon sequestration, they can also increase N_2O emissions. DNDC, a model that predicts CO_2 and N_2O exchange, will be used to forecast the impact of various management practices on the net greenhouse gas emissions in CO_2 equivalent. This model, which relies on episodic rather than average climatic drivers, will be validated for several case studies across Canada. It will then be used to obtain regional and national estimates of N_2O emissions. The regional estimates will be validated using micrometeorological techniques.

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