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Estimation of the impact of climate change on soil carbon sequestration for agricultural soils in Canada

Smith, W.N., Grant, B.B., Desjardins, R.L., Hutchinson, J., Qian, B., Gameda, S. and Vergé X.
Agriculture and Agri-Food Canada, Ottawa, Canada, K1A0C6
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Abstract

The Century model was used to examine the influence of climate change on carbon in agricultural soils in Canada. It predicts that agricultural soils would lose 164 Mt of C by 2100 for a moderate (SRES B2) climate change scenario and 62 Mt C for a moderate-high (IS92a) climate change scenario. Carbon factors associated with changes in management practices that are considered to have the best potential to sequester carbon were also estimated for these two climate change scenarios. There was little difference in factors associated with no-till in western semi-arid soils for a change in climate but in humid soils the C factors were larger with climate change. Carbon factors associated with the conversion of annual crops to permanent grass were lower than for historical data in semi-arid soils because water stress hampered crop production but were higher in humid soils.

Résumé

Le modèle Century a été utilisé pour étudier l'influence du changement climatique sur le carbone des sols Canadiens. Il prédit que les sols agricoles en culture permanente perdraient 164 Mt de leur carbone d'ici à 2100 pour un scénario de changement climatique modéré (SRES B2) et 62 Mt pour un scénario de changement climatique plus important (IS92a). Les facteurs de carbone associés aux changements de pratiques de gestions ayant le meilleur potentiel de séquestration de carbone ont également été estimés pour ces deux scénarios. Il y avait peu de différences pour les facteurs associés à l'absence de labour pour les sols semi-arides de l'Ouest avec les changements climatiques mais pour les sols humides le facteur de carbone était plus grand. Les facteurs associés à la conversion de cultures annuelles en prairies permanentes étaient plus faibles que pour les données historiques pour les sols semi-arides parce que le stress hydrique a entravé la production, mais étaient plus élevés en sols humides.

Introduction

Recent concern of human influence on global climate has resulted in the ratification of the Kyoto protocol. Considering that worldwide, agroecosystems account for approximately 20% of anthropogenic GHG emissions and that the global demand for food continues to increase, one can assume that agricultural GHG emissions will continue to rise. The positive side of this scenario is that the agricultural sector, which is intensively managed, has the potential to sequester carbon in soils through the implementation of improved management practices. However, the problem arises that the potential of management practices are probably only appropriate for present day

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conditions. With global temperatures expected to rise anywhere between 1.4 and 5.8 ^{o}C over the next century (IPCC, 2001) the effect climate change may have on soil carbon is of great interest.

Recent research indicates that increasing temperatures will increase CO_2 emissions through increases in soil respiration (Jenkison et al., 1991; Trumbore et al., 1996; Bellamy et al., 2005; Jones et al., 2005), while other studies show that with rising CO_2 concentrations we can expect carbon inputs to increase as a result of increased plant growth (Ojima et al., 1993; Hamilton et al., 2002). Assessing the combined impact of these two processes is something that needs to be evaluated. Many Canadian studies have already assessed the impact of various management practices (Grant et al., 2004; Smith et al., 2001) on greenhouse gas emissions but have not considered climate change. By using the results of two climate forcing scenarios IPCC IS92a and IPCC SRES B2 as climate inputs for the Century model (Parton et al., 1993, 1987, 1982), one can examine the impact of climate change on soil carbon sequestration for agricultural soils. In this study, we estimate the impact of two climate change scenarios on C stocks in Canada. We also assess the impact of the same climate change scenarios on carbon sequestration rates, for two management practices, for twenty-four locations across Canada. The management practices selected are the conversion from intensive till to no-till and the conversion of annual crop to permanent grass.

Materials and Methods

Climate Scenarios

Two climate change scenarios (years 2001-2100) were derived for twenty-four locations across Canada as well as one historical climate data set for 1951-2000. The first set of predicted meteorological data was generated using the Canadian Coupled Global Climate Model 1 (CGCM1) (Flato et al., 2000) with the IPCC IS92a forcing scenario (Leggett et al., 1992). The IPCC IS92a scenario specifies equivalent GHG concentrations and sulphate aerosol loadings from 1850 to 2100 and atmospheric CO_2 concentration increasing at 1% per year after the year 1990. It is considered to be a mid-range scenario in which global population rises to 11.3 billion by 2100, economic growth averages 2.3% year $^{-1}$ between 1990 and 2100 and a mix of conventional and renewable energy sources are used. The second set of future climate data was derived by global climate model CGCM2 (Flato and Boer, 2001) with the IPCC SRES B2 forcing scenario (Nakicenovic et al., 2000). The SRES B2 scenario is similar to the IS92a scenario except that the SRES B2 scenario envisions slower population growth (10.4 billion by 2100) with a more rapidly evolving economy and more emphasis on environmental protection.

The historical climate for the years 1951-2000 were obtained by interpolating observed climate data of nearby weather stations for the 24 locations across Canada. Daily maximum and minimum temperatures as well as daily precipitation were interpolated from up to 10 weather stations in a search radius of 100 km. To derive the localized future climate scenarios from the original GCM results, 30-year means of daily maximum temperature, minimum temperature and monthly precipitation totals were computed for each month, at each GCM

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grid point for the baseline period 1961-1990 as well as the 1981-2010, 2011-2040, 2041-2070 and 2071-2100 periods. Differences between each of the future 30-yr means and the baseline values were computed for temperatures while ratios where calculated for monthly precipitation totals. These differences were interpolated to each of the 24 locations using an inverse distance squared weighting method. The weighted averaged were computed from surrounding four GCM grids to the location of interest. These values were then applied to the historical daily weather data in the baseline period of 1961-1990 to generate the localized future climate scenarios.

Modeling Soil Carbon

The Century model is a site specific computer simulation model which makes use of simplified relationships of soil-plant-climate interactions to describe the dynamics of soil C and N in grasslands, crops, and forests. It was used to estimate the impact of climate change as predicted by CGCM1 for IS92a and CGCM2 for SRES B2 on soil carbon sequestration from twenty-four locations in Canada. The impact of climate change on some of the most promising management practices that promote soil carbon sequestration was also determined. The twenty-four locations were selected to encompass the major soil groups and textures that are found in agricultural soils in Canada. All model inputs were extracted for each of the selected locations from the Soil Landscape Layer file located in the Soil Landscapes of Canada database version 3.0. These include bulk density, pH, sand silt and clay fractions as well as organic carbon amounts. Native vegetation simulations were run for 5000 years to derive the fractioning of the three carbon pools present in the Century model. Fertilizer-N amendments were applied at the same rates as those detailed in Grant et al., (2004). Two common crop rotations and two prominent management practices were simulated for each of the locations under a historical climate scenario as well as for both the IS92a and SRES B2 scenarios (Table 1). Century simulations for the two climate change scenarios had atmospheric CO_2 concentrations scaled as a linear function from 370 ppmv in the year 2000 to 620 ppmv in the SRES B2 climate scenario and up to 740 ppmv in the IS92a climate scenario. These simulations were compared against the historical scenario that used historical increases in atmospheric CO_2 concentrations up to the year 2000 with no further increases from years 2001-2100. All calculations were reported at the soil group level by averaging the results of the locations that were located in similar soil groups. Soil C factors for changes in management were calculated by taking the difference in the rate of carbon change between the base simulation under conventional tillage and the respective management change under the identical climate scenario (historical, IS92a or SRES B2) over a 20 year duration. Changes in carbon stocks at 2100 were calculated for the base crop rotations for historical climate as well as the two future climate scenarios.

Results and Discussion

Soil Carbon Stocks

Estimates using the Century model for western Canada indicated that for both climate change scenarios under continuous wheat more loss of soil C was predicted than for the historical climate simulations (Table 3). This is presumably because higher soil

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temperatures in the SRES B2 and IS92a scenarios resulted in higher rates of decomposition of organic matter. The loss of soil C was somewhat offset by the increased C input from enhanced crop production. At some locations yields were as much as 15% higher by the year 2100 under the IS92a climate. Crop growth was, however, hampered by less available moisture under the SRES B2 scenario where an additional 9240 kg ha^{-1} of soil C was lost by the year 2100 in the Dark Grey Chernozem. Unlike the IS92a scenario which predicted both higher temperatures and more precipitation, the SRES B2 scenario predicted increased temperatures with minimal increases in precipitation (Table 2). This explains why there were less C input and more soil C loss for the continuous wheat rotation under the SRES B2 scenario. In the wheat-wheat-fallow rotations there was minimal loss of SOC in the SRES B2 climate scenario and actually some gain under the IS92a scenario. Fallow in rotation conserves soil moisture and this would have an impact on crop inputs in systems which have a moisture deficit

Based on results from each crop rotation we scaled up the rates of soil C change for each soil group to estimate C stocks under the historical, SRES B2 and IS92a scenarios. The estimates indicate that agricultural soils in Canada would lose 164 Mt of their carbon by 2100 for a moderate (SRES B2) climate change scenario and 62 Mt for a moderate-high (IS92a) climate change scenario (Table 4). To identify the effect CO_2 fertilization had on C stocks we simulated another set of inputs that had historical increases in atmospheric CO_2 concentrations and then maintained present day concentrations until the year 2100. With no enhanced CO_2 fertilization there was an additional C loss of 90 and 115 Mt in the SRES B2 and IS92a scenarios, respectively.

Soil Carbon Sequestration Factors

Carbon factors estimated using historical climate data ranged from 0.09 to 0.20 Mg C ha^{-1} y^{-1} for conversion of intensive till to no-till for the semi-arid soils in western Canada and from 0.10 to 0.12 Mg C ha^{-1} y^{-1} in the humid soil groups (Table 5). Factors for conversion of annual crop to grassland ranged from 0.27 to 0.59 Mg C ha^{-1} y^{-1} in semi-arid soils and 0.55 to 0.89 Mg C ha^{-1} y^{-1} in humid soils.

For semi-arid soils, C factors for conversion of intensive till to no-till under the SRES B2 and IS92a climate scenarios were similar to the historical factors whereas the no-till factors under climate change in the humid groups were higher. We think that increased temperatures in the spring and fall coupled with the higher soil moisture content in the humid soils resulted in greater decomposition rates in the intensively tilled systems.

The factors for the conversion of annual crop to grassland were lower under the climate change scenarios in semi-arid soils but were higher in humid soils. For semi-arid soils in western Canada soil moisture is a limiting factor for continuous production of perennial grasses. It stands to reason that with increased temperatures and little change in precipitation (Table 2) there would be more evapotranspiration resulting in soil water

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stress and less production. Finally, even though the factor for conversion of annual crops to perennial grass was higher under the SRES B2 and IS92a scenarios in humid soils there was still more loss of carbon in comparison to the historical simulations (Table 3).

Conclusions

The Century model was used to estimate C dynamics under two climate change scenarios at twenty-four locations across Canada. Soil carbon was lost from annual cropping system as a result of higher soil temperatures which leads to enhanced C decomposition rates. Increased crop production from CO_2 fertilization and warmer soils did occur but it could not compensate for the enhanced rate of SOC decomposition in the soil. Crop yields were sometimes limited by soil moisture stress as a result of greater evapotranspiration from the warmer soils. Crop rotations with summer fallow in western Canada lost less or sometimes gained carbon under the climate change scenarios. The climate change scenarios had little influence on C factors for conversion of intensive till to no-till agriculture in semi-arid regions of Canada. Carbon factors for no-till were, however, higher than historical factors in humid regions. When converting from annual cropping to perennial grass, C factors under the climate scenarios were lower than historical values in western Canada whereas they were higher in humid regions. Grass production was hampered by water stress in the semi-arid regions

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Table 1: Soil Groups, crop rotations fertilizer application rates and management practices

Soil Group	Rotation[1]	Fertilizer application rate (kg N ha^{-1})	Management Practices[2]
Brown Chernozem	W, W-W-F	15, 5-15-0	CT, NT, ContG
Dark Brown Chernozem	W, W-W-F	40, 15-40-0	CT, NT, ContG
Black Chernozem	W, W-W-F	70, 40-70-0	CT, NT, ContG
Dark Grey Chernzoem	W, W-W-F	70, 40-70-0	CT, NT, ContG
Grey Luvisol	CCBB, W-W-F	180-180-70-70 40-70-0	CT, NT, ContG

Grey Brown Luvisol	CCBB, CC4HB	180-180-70-70 180-0-0-0-0-70	180-	CT, NT, ContG
Gleysolic	CCBB, CC4HB	180-180-70-70 180-0-0-0-0-70	180-	CT, NT, ContG

1. W, wheat; C; corn; F, summer fallow; H, hay; B, barley.
2. CT, Conventional Tillage; NT, no-till; ContG, conversion to perennial grass

Table 2: Mean annual historical weather data (1951-2000) and climate change scenarios (2070-2100) for eastern and western Canada.

	Scenario	Max Temp ^oC	Min Temp ^oC	precip (mm)
Eastern Canada	Historical	11.92	2.24	873
	SRES B2	14.97	6.19	918
	IS92a	16.66	7.44	988
Western Canada	Historical	9.09	-3.16	440
	SRES B2	13.16	1.38	443
	IS92a	14.32	2.89	532

Table 3: Estimated change in soil organic carbon from 2000-2100

Soil Group	Historical SOC	SRES B2 Difference	IS92a Difference		Historical SOC	SRES B2 Difference	IS92a Difference
		(kg ha^{-1})				(kg ha^{-1})	
semi-arid soils		Cont-Wheat				Wheat-Wheat-Fallow	
Brown Chernozem	67430	-1970	-780		59280	-600	570
DarkBrown Chernozem	87600	-2160	-2210		69360	500	840
Black Chernozem	113910	-9580	-2650		89770	-4490	760
Dark Grey Chernozem	78780	-9240	-3550		59060	-3990	270
humid soils		CC4HB[1]				Wheat-Wheat-Fallow	
Grey Luvisol	60280	-9540	-9130		46910	2350	2260
		CC4HB[1]				CCBB[1]	
Grey Brown Luvisol	124070	-4190	-5260		112380	-5440	-7250
Gleysolic	125520	-3690	-3140		117670	-4980	-4910

1:C,Corn;B, Barley;H,Hay.

Table 4: Estimated impact of climate change scenarios on carbon stocks

Soil group	Crop Rotations	Historical	SRES B2	IS92a
		Mt C	Mt C loss	Mt C loss
Brown Chernzoem	W, WWF	334	-6.8	-0.5

Dark Brown Chernozem	W, WWF	540	-5.7	-4.7
Black Chernozem	W, WWF	1301	-89.9	-1[illegible]
Dark Grey Chernozem	W, WWF	279	-26.8	-6[illegible]
Grey Brown Luvisol	CCBB, CC4HB	380	-15.5	-20.1
Gleysolic	CCBB, CC4HB	325	-11.6	-10.8
Grey Luvisol	CC4HB, WWF	113	-7.5	-7.2
Total			-163.7	-62.0

Table 5: Estimated carbon factors for changes in management for a 20 year duration from 2000-2020

	Conversion to No-till			Conversion to Perennial Grass		
Soil Group	Historical	SRES B2	IS92A	Historical	SRES B2	IS92A
			(Mg C ha^{-1})			
semi-arid soils						
Brown Chernozem	0.09	0.05	0.09	0.59	0.49	0.54
DarkBrown Chernozem	0.11	0.12	0.11	0.48	0.38	0.41
Black Chernozem	0.17	0.14	0.19	0.35	0.29	0.30
Dark Grey Chernozem	0.20	0.17	0.22	0.27	0.24	0.23
humid soils						
Grey Luvisol	0.10	0.25	0.25	0.55	0.70	0.69
Grey Brown Luvisol	0.12	0.15	0.16	0.88	1.02	0.99
Gleysolic	0.11	0.15	0.13	0.89	0.98	1.01