

## ESTIMATED N<sub>2</sub>O AND CO<sub>2</sub> EMISSIONS AS INFLUENCED BY AGRICULTURAL PRACTICES IN CANADA

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**Abstract.** The Denitrification-Decomposition (DNDC) model was used to estimate the impact of change in management practices on N<sub>2</sub>O emissions in seven major soil regions in Canada, for the period 1970 to 2029. Conversion of cultivated land to permanent grassland would result in the greatest reduction in N<sub>2</sub>O emissions, particularly in eastern Canada where the model estimated about 60% less N<sub>2</sub>O emissions for this conversion. About 33% less N<sub>2</sub>O emissions were predicted for a change from conventional tillage to no-tillage in western Canada, however, a slight increase in N<sub>2</sub>O emissions was predicted for eastern Canada. Greater N<sub>2</sub>O emissions in eastern Canada associated with the adoption of no-tillage were attributed to higher soil moisture causing denitrification, whereas the lower emissions in western Canada were attributed to less decomposition of soil organic matter in no-till versus conventional tilled soil. Elimination of summer fallow in a crop rotation resulted in a 9% decrease in N<sub>2</sub>O emissions, with substantial emissions occurring during the wetter fallow years when N had accumulated. Increasing N-fertilizer application rates by 50% increased average emissions by 32%, while a 50% decrease of N-fertilizer application decreased emissions by 16%. In general, a small increase in N<sub>2</sub>O emissions was predicted when N-fertilizer was applied in the fall rather than in the spring. Previous research on CO<sub>2</sub> emissions with the CENTURY model (Smith et al., 2001) allowed the quantification of the combined change in N<sub>2</sub>O and CO<sub>2</sub> emissions in CO<sub>2</sub> equivalents for a wide range of management practices in the seven major soil regions in Canada. The management practices that have the greatest potential to reduce the combined N<sub>2</sub>O and CO<sub>2</sub> emissions are conversion from conventional tillage to permanent grassland, reduced tillage, and reduction of summer fallow. The estimated net greenhouse gas (GHG) emission reduction when changing from cultivated land to permanent grassland ranged from 0.97 (Brown Chernozem) to 4.24 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup> (Black Chernozem) for the seven soil regions examined. When changing from conventional tillage to no-tillage the net GHG emission reduction ranged from 0.33 (Brown Chernozem) to 0.80 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup> (Dark Gray Luvisol). Elimination of fallow in the crop rotation lead to an estimated net GHG emission reduction of 0.43 (Brown Chernozem) to 0.80 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup> (Dark Brown Chernozem). The addition of 50% more or 50% less N-fertilizer both resulted in slight increases in combined CO<sub>2</sub> and N<sub>2</sub>O emissions. There was a tradeoff in GHG flux with greater N<sub>2</sub>O emissions and a comparable increase in carbon storage when 50% more N-fertilizer was added. The results from this work indicate that conversion of cultivated land to grassland, the conversion from conventional tillage to no-tillage, and the reduction of summerallow in crop rotations could substantially increase C sequestration and decrease net GHG emissions. Based on these results a simple scaling-up scenario to derive the possible impacts on Canada's Kyoto commitment has been calculated.

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## 1. Introduction

With its commitment to the Kyoto protocol, Canada has agreed to reduce its greenhouse gas emissions to 6% below 1990 levels by the year 2010. The agriculture sector is responsible for about 10–15% of Canada's greenhouse gas emissions (Desjardins and Riznek, 2000). Because it is intensively managed, this sector is an excellent candidate for helping Canada meet part of its commitment. One of the most cost effective strategies for reducing GHG emissions is through the use of improved management practices. Many of these management practices have already been identified (Lal and Bruce, 1999; Smith et al., 2001). Practices such as adoption of no-tillage, reduction of bare fallow and conversion of croplands to permanent grasslands have frequently been identified as promising management practices to reduce greenhouse gas emissions. However, many of these practices have only been evaluated for their ability to either reduce CO<sub>2</sub> emissions or to increase carbon sequestration. While carbon sequestration in agricultural soils may be beneficial to the environment as well as to crop production, other greenhouse gases must be considered when assessing greenhouse gas mitigation strategies. Nitrous oxide, which has a global warming potential 310 times more than CO<sub>2</sub> must be considered (Watson et al., 1990). As well, emissions of methane from manure and livestock can substantially affect the GHG budget (Desjardins and Riznek, 2000). It is not difficult to perceive how a management practice that succeeds in reducing emissions of one GHG such as CO<sub>2</sub> can lead to increased emissions of another. For example, in a soil with sufficient moisture one would expect that increasing the amount of N-fertilizer applied should lead to greater plant production and thus more carbon sequestered in the soil. However it is also possible that the increase in available N from the added N-fertilizer would increase the amount of N<sub>2</sub>O emitted to the atmosphere, thereby countering any benefits gained from the additional carbon sequestered. Hence it is essential to consider the net emissions of N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> in order to assess the impact of a management practice.

Emissions of N<sub>2</sub>O are influenced by environmental factors such as temperature, rainfall, snowmelt, freezing and thawing, as well as by management practices, such as nutrient application via manure and N-fertilizer, summer fallowing, incorporation of either crops or crop residues, and tillage. The temporal and spatial variability of N<sub>2</sub>O emissions in response to climate and soil conditions make it very difficult to estimate emissions from agricultural sources. Measurements of N<sub>2</sub>O emissions within a field have been found to have a coefficient of variation greater than 150% (Manuela et al., 1999) and even greater variability can be expected between fields. Thus a modeling approach is required to estimate N<sub>2</sub>O emissions over large areas, given the inherent variability of N<sub>2</sub>O emissions over space and time. Drivers of N<sub>2</sub>O emissions are (1) substrate supply, (2) N additions and mineralization-nitrification of organic N, (3) soil water content and (4) temperature (Skiba and Smith, 2000). Each driver can have a large influence on emissions. Accurate estimates of annual N<sub>2</sub>O emissions at the field, regional and country-wide

scale are required in order to compare the impact of management strategies and identify management practices that will lead to lower GHG emissions.

The objectives of this paper are: (1) use a modeling approach to estimate changes in N<sub>2</sub>O emissions from agricultural soils in Canada upon implementation of certain management practices (2) examine the tradeoffs between C sequestration and N<sub>2</sub>O emissions. The following management practices will be examined: the conversion of cultivated land to permanent grassland, the shift from conventional tillage to no-tillage, the application of 50% more or 50% less N-fertilizer, the timing of N-fertilizer application, and the elimination of summerfallow in the crop rotation.

## 2. Methodology

The DeNitrification and DeComposition model (DNDC), consisting of four interacting submodels, thermal/hydraulic, crop growth, decomposition, and denitrification, was used to assess the impact of changes in management on N<sub>2</sub>O emissions across Canada. This process-based model uses readily available input data to predict carbon and nitrogen dynamics in soils over a long time period (Li et al., 1992a,b, 1994, 2000). The DNDC model was previously calibrated with experimental data from eastern and western Canada (Smith et al., 2002). DNDC has also been tested and validated in a scaling-up project comparing model results to estimates using IPCC methodology for the total arable land in China (Li et al., 2001). Control runs of the model, in which conventional tillage was used with various crop rotations within a soil region, were run for the period from 1970 to 2029. Simulations were also carried out in which the management practices were changed in the year 2000. Where applicable, the following changes in management were simulated: (1) addition of forage/pasture in a rotation; (2) conversion of croplands to grasslands; (3) reduction in the area of summerfallow; (4) change in amount of N-fertilizer applied (50% and 150% of normal N-fertilizer application rate); (5) changing time of N-fertilizer application (spring rather than fall), and (6) change from conventional tillage to either no-tillage or minimum-tillage.

Simulations were run for three soil textures (sandy loam, loam, and clay loam) in each of the seven major soil regions in Canada (Figure 1). The soil regions investigated are the Brown Chernozem, Dark Brown Chernozem, Black Chernozem, Dark Gray Chernozem, Gray Brown Luvisol, Gray Luvisol, and Gleysolic soils. Average soil properties such as bulk density, particle size distribution, pH, and initial organic carbon were obtained from the Soil Landscapes of Canada (SLC) polygon database. All simulations were run for two to four commonly used crop rotations in each soil region. Simplification of many of the crop rotations was necessary to provide a means for easy comparison across each of the seven soil regions. The objectives of the studies were not to generate values for every possi-

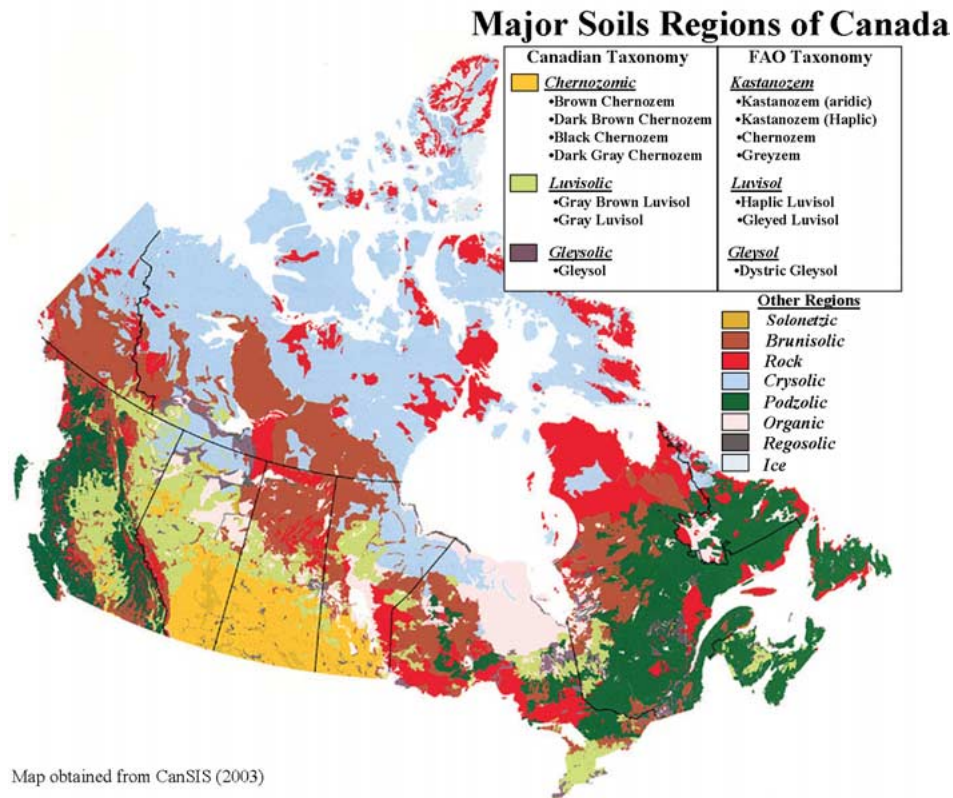


Figure 1. Major soil regions of Canada.

ble permutation of crop rotation and management practice but instead to provide coefficients for the most likely scenarios.

Representative climate data were chosen for each soil region using data from a location that had near average yearly precipitation and temperature within the respective soil region. Daily temperature and precipitation were input into the model for a 30-year simulation period (1970 to 1999). The same weather was repeated for the years 2000 to 2029. Due to the large interannual variations in  $N_2O$  emissions, it was considered necessary to simulate emissions over 30 years to encompass a reasonable range of estimates.

Current N-fertilizer application rates for each crop rotation were taken from Smith et al. (2000) and were applied as business as usual until the year 2029 (Table I). N-fertilizer was applied at 1/3 current rates from 1970 to 1979 and 3/4 current rate from 1980 to 1989, in accordance with Canadian fertilizer consumption records (Korol and Girard, 1996). Thirty percent more N-fertilizer was applied on the no-tillage rotations than on conventional tillage rotations. This was assumed to encompass the initial period in no-tillage systems where additional N-fertilizer is

Table I  
Crop rotations and fertilizer application rates for all control runs

Soil region	Rotation	Fertilizer N application rate (kg ha <sup>-1</sup> y <sup>-1</sup> )
Brown Chernozem	W	15
	W-F	5-0
	W-W-F	5-15-0
	W-P	5-0
Dark Brown Chernozem	W	40
	W-F	15-0
	W-W-F	15-40-0
	W-P	15-0
Black Chernozem	W	70
	W-F	40-0
	W-W-F	40-70-0
	W-P	40-0
Dark Gray Chern/Luvisol	W	70
	W-F	40-0
	W-W-F	40-70-0
	W-P	40-0
Gray Brown Luvisol	M-M-B-B	180-180-70-70
	M-M-H-H-H-H-B	180-180-0-0-0-70
	W-P	70-0
Gray Luvisol	W-W-F	40-70-0
	B-B-H-H-H	70-70-0-0-0-0
Gleysolic	M-M-B-B	180-180-70-70
	B-B-H-H-H	70-70-0-0-0
	W-P	70-0

W – wheat; B – barley; C – canola; F – summer fallow; H – hay; M – maize; P – soybean.

applied to offset any reduction in N availability when switching from conventional tillage. No fertilizer was applied to permanent grasslands.

Coefficients of N<sub>2</sub>O emission for the period 2000 to 2029 were estimated as the average yearly difference in emissions between the new management practice and the control (Table II). Emissions were scaled up for the soil regions by weighting emissions by percent of crop rotation and area of soil texture within the soil regions as follows:

$$N_{\text{Region}} = \sum_{i=1}^t F_i \left( \sum_{j=1}^r F_j R_j \right),$$

where  $N_{\text{Region}}$  =  $\text{N}_2\text{O}$  exchange coefficient for a soil region,  $t$  = number of soil textures,  $F_i$  = fraction of area covered by soil texture,  $r$  = number of crop rotations,  $F_j$  = fraction of area covered by crop rotation, and  $R_j$  is the  $N$  coefficient for a particular crop within a soil texture and soil region. The fraction of area covered by a specific soil texture was derived from the soil landscape database for Canada and the fraction of area covered by each crop rotation was derived from an analysis of the 1996 census data.

Smith et al. (2001) used a similar methodology to estimate soil organic carbon change and net  $\text{CO}_2$  emissions. The CENTURY model was designed to simulate carbon dynamics on a monthly time step and thus was not capable of estimating daily emissions of  $\text{N}_2\text{O}$ . Although DNDC has been used to estimate changes in SOC in long-term field experiments (Li et al., 1997), its primary development focus was towards estimating daily  $\text{N}_2\text{O}$  emissions. Long-term estimates of SOC change using the DNDC model have not been validated for Canadian agriculture. Measures were taken to ensure all assumptions and methodologies remained consistent between both modeling exercises. A comparison to quantify the net radiative changes due to  $\text{N}_2\text{O}$  and  $\text{CO}_2$  for each selected management practice was calculated. To generate the net greenhouse emissions for each practice it was necessary to convert  $\text{N}_2\text{O}$  emissions into  $\text{CO}_2$  equivalents. Each unit of  $\text{N}_2\text{O}$  was considered equivalent to 310 units of  $\text{CO}_2$  (Watson et al., 1990). An updated warming potential for  $\text{N}_2\text{O}$  of 296 units of  $\text{CO}_2$  has been cited by IPCC, (2001) but for comparison purposes previously mentioned values have been used. Once completed, each practice for a specified soil region was summed to estimate the net greenhouse effect for both  $\text{N}_2\text{O}$  and  $\text{CO}_2$  emissions (Table III).

### 3. Results and Discussion

The DNDC model was used to estimate the impact on  $\text{N}_2\text{O}$  emissions for changes in agricultural management practices in Canada beyond the year 2000. Average  $\text{N}_2\text{O}$  emissions coefficients for the various soil regions, soil textures, and appropriate crop rotations as a result of changes in management practices are presented for the period 2000 to 2029 (Table II). The average base or control  $\text{N}_2\text{O}$  emissions for the 2000–2029 period were estimated at  $1.49 \text{ kg N}_2\text{O-N ha}^{-1} \text{ y}^{-1}$ . As expected the Gleysolic and Gray Brown Luvisol soil regions have the greatest nitrous oxide emissions. These soil regions are mainly located in eastern Canada where they receive more precipitation and more nutrients via fertilizer and manure. Due to less rainfall,  $\text{N}_2\text{O}$  emissions in western Canada were generally less than in eastern Canada (Figure 2). About 40% of the total emissions from agricultural soils in

Table II

Average simulated N<sub>2</sub>O exchange coefficients for various soil regions and crop rotations, due to changes in management practices for the period between 2000 to 2029

		Change in N <sub>2</sub> O emissions (kg N <sub>2</sub> O-N/ha/y)						
	Crop rotation	Control <sup>a</sup>	No-till	Reduced fallow	150% fert.	50% fert.	Fall fert.	Perm grass
Brown	WF	0.86	-0.50	-0.39	0.10	-0.02	0.03	-0.37
Chernozem	WWF	0.62	-0.23	-0.17	0.20	-0.05	0.07	-0.16
	W	0.47	0.02		0.39	-0.07	0.18	0.02
	WP	0.68	-0.03		0.11	-0.02	0.04	-0.14
	<b>Average</b>	<b>0.68</b>	<b>-0.23</b>	<b>-0.25</b>	<b>0.17</b>	<b>-0.04</b>	<b>0.07</b>	<b>-0.19</b>
Dark Brown	WF	1.25	-0.67	-0.47	0.08	-0.03	0.09	-0.58
Chernozem	WWF	1.01	-0.36	-0.2	0.26	-0.05	0.18	-0.30
	W	0.87	-0.23		0.58	-0.21	0.47	-0.16
	WP	1.10	-0.19		0.13	-0.04	0.06	-0.28
	<b>Average</b>	<b>1.16</b>	<b>-0.41</b>	<b>-0.3</b>	<b>0.28</b>	<b>-0.08</b>	<b>0.21</b>	<b>-0.37</b>
Black	WF	1.40	-0.73	-0.49	0.27	-0.03	0.09	-0.64
Chernozem	WWF	1.09	-0.33	-0.12	0.35	-0.10	0.46	-0.25
	W	1.10	-0.40		0.84	-0.36	0.77	-0.25
	WP	1.35	-0.26		0.40	-0.15	0.20	-0.33
	<b>Average</b>	<b>1.16</b>	<b>-0.36</b>	<b>-0.09</b>	<b>0.55</b>	<b>-0.21</b>	<b>0.51</b>	<b>-0.29</b>
Dark Gray	WF	2.00	-1.15	-0.8	0.11	-0.02	0.21	-0.96
Luvisol	WWF	1.50	-0.55	-0.31	0.35	-0.08	0.61	-0.32
	W	1.30	-0.51		0.88	-0.33	1.54	-0.15
	WP	2.19	-0.61		0.30	-0.13	0.52	-0.69
	<b>Average</b>	<b>1.58</b>	<b>-0.58</b>	<b>-0.21</b>	<b>0.54</b>	<b>-0.18</b>	<b>0.94</b>	<b>-0.36</b>
Gray	BBHHH	1.43	0.24		0.24	-0.18		-0.78
Luvisol	WWF	2.05	-0.36	-0.45	0.54	-0.40		-1.39
	<b>Average</b>	<b>1.74</b>	<b>-0.06</b>	<b>-0.45</b>	<b>0.39</b>	<b>-0.29</b>		<b>-1.08</b>
Gray Brown	BBHHH	1.75	0.06		0.33	-0.17		-1.08
Luvisol	MMBB	3.22	0.86		1.49	-1.28		-2.29
	BP	2.20	-0.06		0.34	-0.35		-1.22
	<b>Average</b>	<b>2.43</b>	<b>0.36</b>		<b>0.80</b>	<b>-0.65</b>		<b>-1.59</b>
Gleysolic	BBHHH	2.25	-0.04		0.27	-0.19		-1.33
	MMBB	3.59	0.60		1.47	-1.23		-2.37
	BP	2.67	-0.25		0.47	-0.30		-1.32
	<b>Average</b>	<b>2.87</b>	<b>0.18</b>		<b>0.79</b>	<b>-0.63</b>		<b>-1.74</b>
<b>Coefficient for Canada</b>			<b>-0.26</b>	<b>-0.20</b>	<b>0.48</b>	<b>-0.23</b>	<b>0.42</b>	<b>-0.56</b>
<b>Mean BAU Emission Rate</b>		<b>1.49</b>						

<sup>a</sup> Denotes base simulation with conventional tillage for the period between 1970 to 2029.

Negative values indicate less emissions and positive indicate more emissions.

Reduced fallow is relative to W.

. Increase and decrease in fertilizer only represents N-fertilizer application.

Addition of pulse indicates that the rotation converts to WP in 2000.

W – wheat; H – hay; B – barley; F – fallow; M – maize; P – soybean.

Table III

Average CO<sub>2</sub> and N<sub>2</sub>O exchange coefficients due to changes in agricultural management practices (10-year average starting in 2000)

	No-tillage	Eliminate fallow	150% fertilizer	50% fertilizer	Fall fertilizer	Permanent grassland
<i>(A) N<sub>2</sub>O coefficients (Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup>)</i>						
Brown Chernozem	-0.11	-0.12	0.08	-0.02	0.03	-0.09
Dark Brown Chernozem	-0.20	-0.15	0.14	-0.04	0.10	-0.18
Black Chernozem	-0.18		0.27	-0.10	0.25	-0.14
Dark Gray Luvisol	-0.28	-0.10	0.26	-0.09	0.46	-0.18
Gray Luvisol	-0.03		0.19	-0.14		-0.53
Gray Brown Luvisol	0.17		0.39	-0.32		-0.78
Gleysolic	0.08		0.39	-0.31		-0.85
<i>(B) CO<sub>2</sub> coefficients (Mg CO<sub>2</sub> ha<sup>-1</sup> y<sup>-1</sup>)</i>						
Brown Chernozem	-0.22	-0.31	-0.04	0.03	0.00	-0.88
Dark Brown Chernozem	-0.44	-0.65	-0.16	0.16	0.04	-1.15
Black Chernozem	-0.54		-0.08	0.11	0.03	-3.30
Dark Gray Luvisol	-0.52	-0.51	-0.00	0.00	0.00	-4.06
Gray Luvisol	-0.52		-0.46	0.53		-1.60
Gray Brown Luvisol	-0.71		-0.50	0.64		-1.79
Gleysolic	-0.48		-0.18	0.43		-1.51
<i>(C) Combined CO<sub>2</sub> and N<sub>2</sub>O coefficients (Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup>)</i>						
Brown Chernozem	-0.33	-0.43	0.04	0.01	0.03	-0.97
Dark Brown Chernozem	-0.64	-0.80	-0.03	0.12	0.14	-1.33
Black Chernozem	-0.72		0.19	0.01	0.28	-3.44
Dark Gray Luvisol	-0.80	-0.61	0.26	-0.09	0.46	-4.24
Gray Luvisol	-0.55		-0.27	0.39		-2.13
Gray Brown Luvisol	-0.54		-0.11	0.33		-2.56
Gleysolic	-0.40		0.21	0.12		-2.36
Canada	-0.61	-0.56	0.08	0.08	0.23	-2.55

Negative values indicate a net reduction in GHG emissions.

Positive values indicate a net increase in GHG emissions.

Canada were from eastern soils, although they represent about 20% of the total land area.

Several of the management practices examined including reduced tillage, reduction of fallow, reduction in the amount of N-fertilizer application, and conversion from croplands to grassland resulted in less overall N<sub>2</sub>O emissions than did the

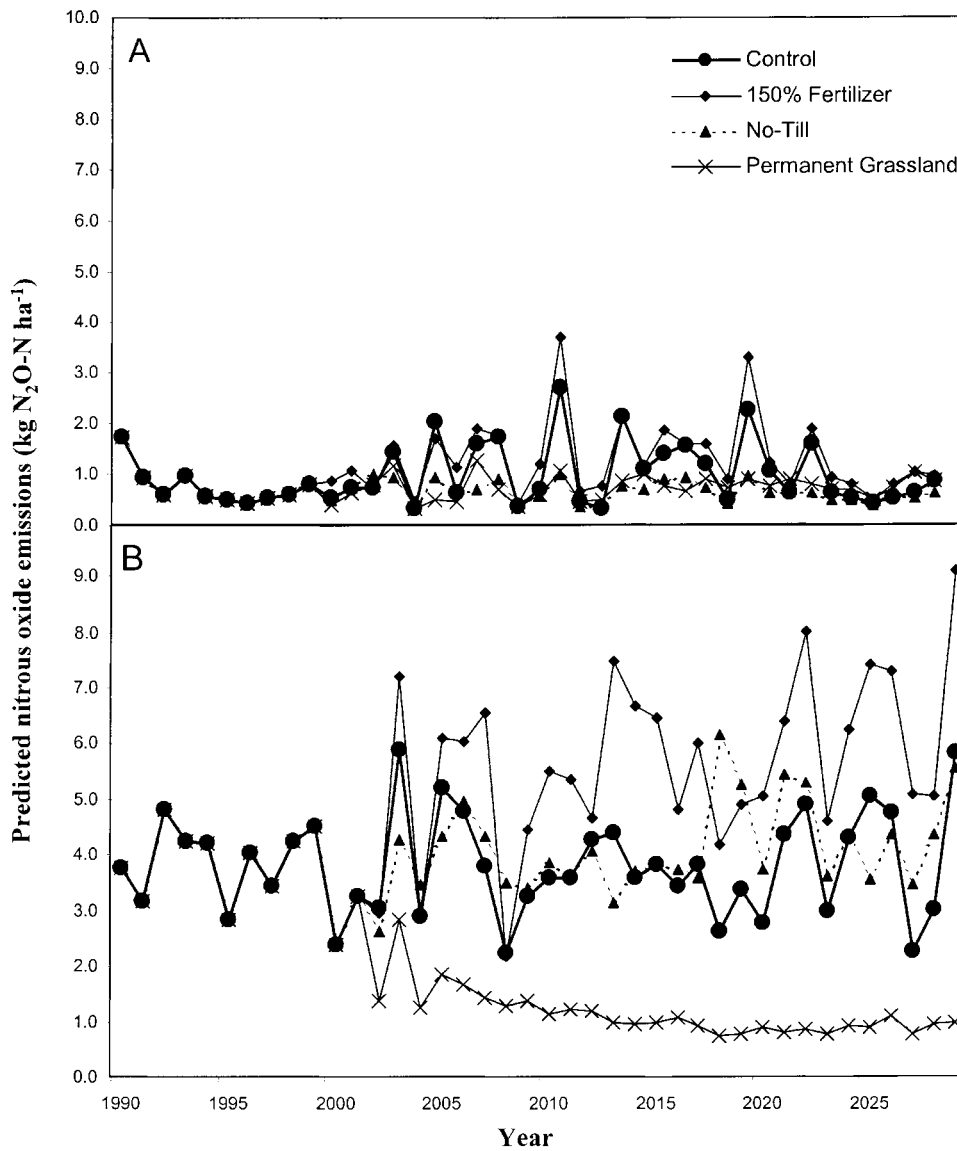


Figure 2. Model estimates of the influence of management changes implemented in the year 2000 on N<sub>2</sub>O-N emissions for a Western (A) and an Eastern (B) soil (1990–2029).

control (Table II). The derived coefficients for N<sub>2</sub>O emissions from this project and coefficients of CO<sub>2</sub> emissions from Smith et al. (2001) are summarized in CO<sub>2</sub> equivalents in Tables IIIa,b respectively. These coefficients were combined to estimate the net radiative changes in GHG emissions upon implementation of a change in management practice in the year 2000 (Table IIIc).

The management practices that showed the greatest potential to reduce the net GHG emissions were permanent grassland, reduced tillage, and elimination of fallow in crop rotations at 2.55, 0.61 and 0.56 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup>, respectively. One must remember that there is a finite capacity for the soils to sequester carbon while the reduction in N<sub>2</sub>O emissions lasts as long as the management scenario continues. Thus it is important to assess the contribution of each gas to the combined net greenhouse gas emissions over a long period of time.

### 3.1. NO-TILLAGE

Change of management from conventional to no-tillage in 2000 resulted in 17% less emissions of N<sub>2</sub>O, on a weighted average in Canada, over 30 years (Table II). The results from DNDC indicated that soil regions in western Canada emitted less N<sub>2</sub>O upon introduction of no-tillage agriculture, whereas most of the simulations in the east showed a small increase in emissions (Figures 2a,b). Lemke et al. (1999) found that N<sub>2</sub>O emissions from Alberta fields under no-tillage had similar or lower annual emissions than those under conventional tillage. Greater precipitation in the east combined with higher soil water content under no-till management was believed to be responsible for this increase. Ball et al. (1999) found that reduced gas diffusivity and air-filled porosity, caused by heavy rainfall resulted in periods of low CO<sub>2</sub> fluxes and high N<sub>2</sub>O fluxes. As well, Rudaz et al. (1999) found that the largest emission rates of N<sub>2</sub>O and N<sub>2</sub> were measured when water filled pore space was above 70–80%. Under no-tillage management model results indicate that western soils will less frequently reach soil water contents that promote the production of N<sub>2</sub>O as compared to eastern soils. Tilling soil disturbs structure, increases aeration and releases more substrates for decomposition. In the drier western soils, where production of N<sub>2</sub>O through denitrification is limited, the increased decomposition of organic matter through conventional tillage may result in more nitrification and thus more N<sub>2</sub>O emissions than under no-till agriculture. Also, more residual nitrogen is available during the fall and spring periods under conventional tillage resulting in more spring N<sub>2</sub>O emissions. Assuming this is the case, no-till management should have a greater benefit in the dryer soil regions as research has found that in these dryer regions the implementation of no-till can significantly increase carbon sequestration. A review by Janzen et al. (1998b), where 11 long term experimental sites in Canada were examined, indicates that there is an average C sequestration of 0.16 Mg C ha<sup>-1</sup> y<sup>-1</sup> on conversion to no-tillage agriculture, whereas comparable values derived from CENTURY averaged 0.13 Mg C ha<sup>-1</sup> y<sup>-1</sup> (Smith et al., 2001). Recently, VandenBygaart and Gregorich, (2003) calculated from numerous experimental data that the average rate of SOC storage for western Canada was 0.32 ± 0.15 Mg C ha<sup>-1</sup> y<sup>-1</sup> which is more than 2 times greater in magnitude than CENTURY estimates. They did however find that average rate of SOC change in no-till experiments for all experimental sites in Canada were only 0.05 ± 0.16 Mg C ha<sup>-1</sup> y<sup>-1</sup>. It appears that CENTURY

underestimates SOC gains for western Canada and overestimates no-till related C sequestration rates in eastern Canada. Hence, in western Canada the no-till practice may be more beneficial in reducing net GHG emissions than indicated in the results.

For Canada, the average combined net GHG reduction when changing the control runs to no-till was estimated at 0.61 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup>. This practice was potentially the second highest in its ability to reduce net GHG emissions behind conversion to permanent grassland. It should be noted that changes in the amount of carbon sequestered from no-till had a much larger impact on reducing the net GHG emissions than reductions in the amount of nitrous oxide emitted for the same practice (Tables IIIa,b). In fact over the 10 year period from 2000 to 2010, carbon was on average about 3 times more influential than N<sub>2</sub>O for the no-tillage management practice.

### 3.2. PERMANENT GRASSLAND

Conversion of marginal land to permanent grassland has garnered a lot of interest in recent years. Although its application may be more limited than a practice such as no-till, the potential of improving soil quality significantly while reducing GHG emissions is well recognized. It has been reasoned that soils that are returned to the 'native' conditions should eventually approach SOC contents similar to corresponding uncultivated sites (Janzen et al., 1998a). Because of loss in fertility through erosion, salinization and other soil degrading processes, some soils can no longer be returned to their level of carbon achieved prior to cultivation. CENTURY predicts that the potential gains from the introduction of permanent grassland average 0.62 Mg C ha<sup>-1</sup> y<sup>-1</sup> for Canadian soils. In an independent literature review Conant et al. (2001) found that the average for 23 experiments located worldwide showed a potential gain of 1.01 Mg C ha<sup>-1</sup> y<sup>-1</sup> for the conversion of cultivated land to permanent grassland.

Management change to permanent grassland in the year 2000 resulted in lower N<sub>2</sub>O emissions in all soil regions. Emissions were reduced more in frequently fallowed systems. Permanent grassland reduces soil water available for mineralization/nitrification and denitrification. The emissions reductions were considerably greater in eastern Canada where more fertilizer is applied to crops, and where more precipitation occurs. Emissions from the Gray Brown Luvisol, Gray Luvisol, and Gleysolic soil regions are reduced to about 40% of the emissions prior to the management change. These results correspond with measurements made by several researchers. On most of his sampling dates Choudhary et al. (2001, 2002) found that croplands under no-tillage and conventional tillage had significantly higher N<sub>2</sub>O emissions than grasslands.

For Canada, the average combined net GHG emission reduction when converting from cultivated land to permanent grassland was approximately 2.55 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup>. Change to permanent grassland resulted in substantially more

carbon being stored in the first 10 years after the change in management. It also caused the largest reduction in the net GHG of all the investigated management scenarios. As for the impact each gas had on the total net GHG reduction, carbon is responsible for most of the effect. Soil organic carbon increases had up to a 40 times greater impact than the corresponding decreases in N<sub>2</sub>O emissions. These gains will decline as carbon approaches its native SOC levels. Nitrous oxide emissions will continue to contribute to global warming after soils have reached equilibrium in carbon storage. Note that CH<sub>4</sub> and N<sub>2</sub>O emissions associated with livestock were not factored into this comparison.

### 3.3. INFLUENCE OF N-FERTILIZER

It is well known that one of the driving factors in the production of N<sub>2</sub>O is the availability of mineral N (Bouwman, 1990; Eichner, 1990; Granli and Bockman, 1994; Mosier, 1994). It has also been demonstrated that increased N<sub>2</sub>O emissions will be observed with the application of N-fertilizer, assuming conditions are suitable for denitrification (Skiba and Smith, 2000). With the addition of 50% more N-fertilizer, higher N<sub>2</sub>O fluxes were predicted for all regions. In dry western soils, plant uptake of the additional N applied is sometimes minimal due to low availability of water thus leaving more mineral N available for nitrification and denitrification. However, soil water contents are often too low for substantial denitrification to occur. Also the addition of N-fertilizer as described in the methodology was relative to the normal application for each soil region. In the case of the Brown soil zone this equates to only a 2.5 kg N ha<sup>-1</sup> addition for the WF rotation whereas in the eastern soil zones the similar increase equated to a 90 kg N ha<sup>-1</sup> addition. With these N-fertilizer rates it is not unrealistic to expect higher N<sub>2</sub>O emissions from the eastern soils even though the potential for uptake of mineral N by the crops is greater in the east. The simulations suggested that the introduction of an additional 50% N-fertilizer into cropland would result in 22 to 47% more emissions of N<sub>2</sub>O across Canada with a weighted average of 32% more emissions, with emissions increasing with soil moisture. Likewise reduction by 50% N-fertilizer application resulted in 5 to 27% less N<sub>2</sub>O emissions with an average of 16% less emissions. The greatest changes occurred in the continuously cropped areas where more N-fertilizer was applied. Up to 1.49 kg N<sub>2</sub>O-N ha<sup>-1</sup> y<sup>-1</sup> more emissions of N<sub>2</sub>O occurred after addition of 50% more N-fertilizer to the maize-maize-barley-barley rotation for the eastern Gray Brown Luvisol (Table II). A large percentage increase was predicted for continuous wheat in western Canada.

For Canada, the average combined net GHG increase when changing the base runs to 150% N-fertilizer application was 0.08 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup>. There was a net reduction in GHG emissions only in the Gray Brown and Gray Luvisolic soil regions (Table IIIc). For those two soils, the increase in the amount of carbon sequestered was enough to offset the increase in N<sub>2</sub>O emissions associated with this practice. The average combined net GHG emissions increased by 0.08 Mg CO<sub>2</sub>

equiv. ha<sup>-1</sup> y<sup>-1</sup> when changing the base runs to the 50% N-fertilizer scenario. The benefit associated with the reduction of N<sub>2</sub>O emissions was not enough to offset the decreased carbon sequestration through less crop yields. According to the majority of the results, current N-fertilizer rates seem to be near or at the most optimal rates with respect to net GHG emissions. Hence, in order to reduce net GHG emissions N use efficiency should be increased, thereby reducing the amount of available N for denitrification. Greenhouse gas emissions associated with production of fertilizer are not included in the calculations.

#### 3.4. TIMING OF N-FERTILIZER

Fall fertilizer application of nitrogen is used on a number of farms in western Canada though the impacts for GHG emissions are not fully understood. The reasons behind using such a practice are many. Firstly, farmers can curb some of the effects of inflationary fertilizer prices in the spring through the purchase of fertilizers in the fall as well as avoiding the need for specialized equipment for fertilizing and seeding simultaneously in the spring (Malhi et al., 2001). There is some debate as to whether the loss of N is substantial during the winter months. Malhi et al. (2001) maintain that soils on the Great Plains in Canada are essentially frozen from mid-November to mid-March and losses of N from frozen soils are minimal. So long as soils remain frozen nitrogen leaching should not be much of a problem, however during spring thaw, any nitrogen near the surface has the potential to be lost through denitrification (Walsh, 1970).

On a sandy loam soil in Switzerland, Rudaz et al. (1999) observed higher N<sub>2</sub>O losses when fertilizer was applied at the end of the growing season versus a spring application. This is consistent with coefficients generated using DNDC for fall application. DNDC predicts higher N<sub>2</sub>O emissions for all the western soils with respect to fall N-fertilizer application. The most substantial emissions occur in the Black Chernozems and Dark Gray Luvisols at 0.25 and 0.46 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup>. This corresponds with these soils having the largest amounts of N-fertilizer applied and thus allowing the greatest rates of denitrification due to high concentrations of nitrogen near the surface during spring thaw. It should be noted that, in the test simulations, DNDC would predict high amounts of leaching of nitrogen (up to 30%) if the N-fertilizer was placed on the field too early in the fall. As a result of fall N-fertilizer application CENTURY predicted lower rates of carbon sequestration (Table IIIb). Small losses of mineral N through leaching and denitrification during the winter months and spring thaw resulted in slightly lower crop production.

For Canada, the average combined net GHG increase when changing the base runs to fall N-fertilizer application was estimated as 0.23 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup>. A negative effect on GHG emissions was predicted for both CO<sub>2</sub> and N<sub>2</sub>O. Unfortunately, for some farmers, the economic benefit and appealing labor redistribution of this management practice outweigh any potential negative environmental impacts.

### 3.5. REDUCTION IN SUMMERFALLOW

Intensification of cropping practices through the reduction of fallow to increase soil carbon sequestration has frequently been identified as one of the better management strategies. Follet and McConkey (2000) estimated the C sequestration rates for land removed from fallow would range between 0.20–0.30 Mg C ha<sup>-1</sup> y<sup>-1</sup> in Canada. This is somewhat higher than the CENTURY derived coefficients of 0.14 Mg C ha<sup>-1</sup> y<sup>-1</sup>. Since CENTURY has some difficulty in generating comparable crop production values in the dryer western soil regions, the possible underestimation of carbon sequestration by the model when moving towards a more intensive crop rotation is not surprising. The tradeoffs for reducing fallow in the crop rotation on N<sub>2</sub>O emissions are not as easy to discern. When fallow was eliminated from the crop rotation in the year 2000, DNDC predicted 9% less emissions of N<sub>2</sub>O, when compared to the control simulations. The most benefit was observed in the Gray Luvisol and Brown Chernozems at 0.22 and 0.14 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup> respectively (Table IIIa). Initially it was thought that more intensive cropping would likely lead towards greater emissions of N<sub>2</sub>O through the availability of higher concentrations of mineral N as a result of increased fertilizer application. However, in the dryer western soils very little N-fertilizer is applied and the crop generally uses most of the available N. In fallow years, N accumulates through mineralization of organic matter and the soil moisture increases (Smith et al., 2002). Other researchers have observed higher N<sub>2</sub>O emissions during the fallowing of agricultural land. In sub-humid soils in Saskatchewan, Lemke et al. (2001) reported variable emissions between continuous wheat and wheat-fallow rotations with more emissions sometimes occurring from the wheat-fallow plots than from the continuous wheat plots. As well, Chouldhary et al. (2001) noticed that during the fallow year there was an increase in N<sub>2</sub>O emissions in both of his long-term cultivated fields. In Canada, most of the fallow reduction would occur in these dryer soil regions. For Canada, the average combined net GHG emissions decreased by 0.56 Mg CO<sub>2</sub> equiv. ha<sup>-1</sup> y<sup>-1</sup> when one eliminates fallow years. Not only is there the benefit of reducing GHG emissions but also where feasible the movement towards more intensive cropping systems may make economical sense for farmers.

### 3.6. POSSIBLE IMPACTS ON THE KYOTO COMMITMENT

As part of its Kyoto commitment, Canada has agreed to reduce its net GHG emissions to 6% below 1990 values by the period 2008–2012. This is likely to be a difficult task considering that under a business as usual scenario (BAU), GHG emissions are predicted to increase substantially. Therefore it is important for the various sectors to find ways to reduce their emissions. In agriculture, due to the diversity of soil climatic conditions, it is unlikely that any one particular management practice would be suitable for all of Canada. The model results discussed in the previous sections and presented in Table IIIc indicate that conversion from

convention tillage to no-tillage, the conversion of cropland to permanent grassland and the reduction of summerfallow in crop rotations are three management practices that have a considerable potential to reduce GHG emissions in Canada. Under a high adoption situation, some simplistic scaling up calculations for these three practices can be completed. It has been estimated by Boehm et al. (2003) that croplands in 1990 were a net source of GHG emissions of approximately 20.1 Tg CO<sub>2</sub> equiv. y<sup>-1</sup>. Furthermore, under a BAU scenario, croplands in 2008 are projected to be a net source of GHG emissions of approximately 14.1 Tg CO<sub>2</sub> equiv. y<sup>-1</sup>. The reduction in GHG emissions is attributed to an increase in the amount of no-tillage management as well as a reduction in summerfallow since 1990. Following this, it was assumed that the total area in no-till management would increase from 28% under BUA to 60% by the year 2008. Using the net CO<sub>2</sub> equiv. coefficients in Table IIIc a net GHG emission reduction of approximately 8.0 Tg CO<sub>2</sub> equiv. y<sup>-1</sup> is estimated for this practice. It was assumed that 1 Mha of cropland could be converted to permanent grassland in Western Canada. Applying this area evenly across the five major soil regions located in the west an estimated net GHG reduction of 2.9 Tg CO<sub>2</sub> equiv. y<sup>-1</sup> was calculated. For the summerfallow scenario it was assumed that an additional 0.8 Mha of fallow could be eliminated from the semi-arid chernozems of western Canada. This would drive the estimated area of summerfallow down to approximately 3.9 Mha for Canada and a net GHG emission reduction of 0.5 Tg CO<sub>2</sub> equiv. y<sup>-1</sup> would result. Summing the net GHG emission reduction for all three of these management practices under their respective high adoption scenarios produces an estimated net GHG emission reduction of 11.4 Tg CO<sub>2</sub> equiv. y<sup>-1</sup> for Canada. This would reduce croplands from being a net source of GHG emissions of 14.1 to 2.7 Tg CO<sub>2</sub> equiv. y<sup>-1</sup> by the year 2008. It should be emphasized that the coefficients are only derived for a 10-year period following changes in management practices for the year 2000. These coefficients will decrease in magnitude as time progresses due to the finite capacity of soils for storing carbon. Only the N<sub>2</sub>O component of the coefficients would continue to have significant impact over the long-term. Hence, agricultural management practices will have a large impact on the short-term reduction in net GHG emissions, but will have a diminished impact on reducing emissions over time.

#### 4. Conclusions

The implementation of more sustainable management practices is one of the better methods of reducing GHG emissions, specifically CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>. While substantial research has been completed for specific gas emissions on different management scenarios, the tradeoffs between various gases has not been determined. Assessing the impacts of various management practices on different crops and soil types becomes very difficult through the explicit use of experimental data. The requirement for process-based models becomes evident when one examines

the number of permutations of scenarios possible. Using two process-based models that had been previously calibrated for Canadian conditions, the influence of various management practices on N<sub>2</sub>O and CO<sub>2</sub> emissions can be examined and the net changes of emissions of these gases can be estimated.

From the six management practices investigated only three proved to have a net reduction in GHG emissions: (1) conversion of cropland to grassland, (2) conversion of conventional tillage to no-tillage, and (3) reduction of summer fallow from the crop rotation. The estimated combined net reduction in GHG emissions in CO<sub>2</sub> equivalents when changing the base rotations to grassland ranged from 0.97 to 4.24 Mg CO<sub>2</sub> ha<sup>-1</sup> y<sup>-1</sup> in the Brown and Black Chernozem soils, respectively. The conversion to grassland had the largest influence in the net GHG emission reduction for Canadian soils of all the management practices studied. For Canada, the average combined net GHG emission reduction in CO<sub>2</sub> equivalents when changing the base runs to no-till was 0.61 Mg CO<sub>2</sub> ha<sup>-1</sup> y<sup>-1</sup>. The reduction of summerfallow resulted in a net GHG emission reduction in CO<sub>2</sub> equivalents of 0.56 Mg CO<sub>2</sub> ha<sup>-1</sup> y<sup>-1</sup> for Canada. The changes in N-fertilizer application rates in the year 2000 to either 50% more or less N-fertilizer application generally resulted in small increases in combined CO<sub>2</sub> and N<sub>2</sub>O emissions. There was a tradeoff in emissions with greater N<sub>2</sub>O when 50% more N-fertilizer was added but there was a comparable increase in carbon storage. An increase in the net GHG emissions was found from addition of N-fertilizer in the fall when compared to spring application. This was due mostly to the increased N<sub>2</sub>O emissions associated with spring thaw and the associated denitrification of the nitrogen from the N-fertilizer.

The results from this research indicate that there are important interactions between C sequestration in agricultural soils and N<sub>2</sub>O emissions. Hence, when making policy decisions regarding the influence of management practices on greenhouse gas emissions it is of utmost importance to examine the combined emissions of N<sub>2</sub>O and CO<sub>2</sub>.

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