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Estimates of the interannual variations of N_2O emissions from agricultural soils in Canada

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Abstract

The DNDC model was used to estimate direct N_2O emissions from agricultural soils in Canada from 1970 to 1999. Simulations were carried out for three soil textures in seven soil groups, with two to four crop rotations within each soil group. Over the 30-year period, the average annual N_2O emission from agricultural soils in Canada was found to be 39.9 Gg N_2O–N, with a range from 20.0 to 77.0 Gg N_2O–N, and a general trend towards increasing N_2O emissions over time. The larger emissions are attributed to an increase in N-fertilizer application and perhaps to a trend in higher daily minimum temperatures. Annual estimates of N_2O emissions were variable, depending on timing of rainfall events and timing and duration of spring thaw events. We estimate, using DNDC, that emissions of N_2O in eastern Canada (Atlantic Provinces, Quebec, Ontario) were approximately 36% of the total emissions in Canada, though the area cropped represents 19% of the total. Over the 30-year period, the eastern Gleysolic soils had the largest average annual emissions of 2.47 kg N_2O–N ha^{-1} y^{-1} and soils of the dryer western Brown Chernozem had the smallest average emission of 0.54 kg N_2O–N ha^{-1} y^{-1}. On average, for the seven soil groups, N_2O emissions during spring thaw were approximately 30% of total annual emissions. The average N_2O emissions estimates from 1990 to 1999 compared well with estimates for 1996 using the IPCC methodology, but unlike the IPCC methodology our modeling approach provides annual variations in N_2O emissions based on climatic differences.

Introduction

By ratifying the Kyoto Protocol, Canada has committed to reduce its greenhouse gas (GHG) emissions to 6% below the 1990 levels by 2010. The agricultural sector is responsible for approximately 10% of the GHG emissions in Canada (Desjardins and Riznek 2000). Of the three gases, CO_2, CH_4 and N_2O, influenced by agricultural activities, current estimates indicate that N_2O emissions from agricultural soils represent the largest source of GHGs from the sector (Desjardins and Riznek 2000). Unfortunately, N_2O fluxes are also the most difficult to estimate due to the complexity of the processes controlling N_2O production coupled with the strong influence that interannual weather variability has on emissions. N_2O emissions are influenced by environmental factors such as rainfall, temperature, snowmelt, freezing and thawing, as well as management practices such as manure and fertilizer application, incorporation of either crops or crop residues, and tillage. The high temporal and spatial variability of N_2O emissions in response to climate and soil conditions makes it very difficult to quantify emissions from agricultural sources. Chamber measurements of N_2O emissions provide satisfactory data on a site-specific basis; however, because of the diversity in soil, as well as climate and crop management, it is difficult to extrapolate this data to a larger scale. Accurate estimates of annual N_2O emissions at the field, regional and country-wide scale are required to: (i) establish baseline values; (ii) compare current management strategies and identify beneficial management practices; and (iii) evaluate and monitor the impact of new management practices. Scaling-up techniques and simulation models that are dynamic enough to account for the spatial and temporal variability inherent to N_2O emissions are urgently needed. Appropriate models could improve the reliability of temporal and spatial integrations, and help identify knowledge gaps. They are also needed as predictive tools for assessing the influence of changing management and/or climate on N_2O emissions.

There have been few attempts to model N_2O emissions from agricultural soils on a national level (Li et al. 2001). Model requirements for data and large variability in climate, soils, and N_2O emissions can result in high uncertainty in predictions. The DNDC model simulates N_2O emissions under a wide variety of management scenarios using readily available input data. The model is, however, less rigorous in predicting soil–water dynamics than some other N models such as ECOSYS (Grant and Pattey 1999) and Expert-N (Engel and Priesack 1993).

The objectives of this paper are to estimate daily and annual N_2O emissions from agricultural soils in Canada from 1970 to 1999 and to determine the influence of rainfall, temperature, and varying N-fertilizer application rates on the interannual variations of N_2O emissions. We will be dealing only with direct emissions from agricultural soils. The indirect N_2O emissions from runoff, manure holding systems, volatilization and deposition of NH_3 and NO_X will not be dealt with in this paper.

Description of DNDC

The DNDC (DeNitrification DeComposition) model by Li et al. (1992a,b, 1994) and Li (2000) provides daily and annual N_2O emissions from agricultural soils, using readily available input data. The model consists of four interacting submodels (Figure 1). A thermal/hydraulic submodel calculates soil temperature and moisture profiles and soil water fluxes from daily air temperature and precipitation data and soil texture. The physical–chemical processes have been modified to include freezing and thawing and snow insulation. A crop growth submodel simulates growth of various crops, N fixation by leguminous crops, and predicts biomass and N content of grain, stalk and root. Crop growth is limited by nitrogen and water availability to roots. Transpiration is calculated from crop growth and a crop-specific water-use-efficiency parameter. A decomposition submodel has four soil carbon pools – litter, labile humus, passive humus, and microbial biomass. Each pool has a fixed decomposition rate and a fixed C:N ratio. Decomposition rates are influenced by soil texture, soil temperature and moisture, and potentially by nitrogen limitations. The denitrification submodel operates on an hourly time-step and is activated when soil oxygen availability decreases as a result of high soil–water contents or freezing temperatures. Oxygen diffusion into the soil is inhibited by high soil–water contents or frozen soils. An oxidation–reduction potential is calculated using soil organic matter content as a proxy for oxygen consumption. Inputs are required in three different areas: (1) climate files consisting of daily cumulative precipitation and maximum and minimum daily air temperatures; (2) soil properties including texture, bulk density, pH, and total organic carbon; and (3) pertinent management variables such as crop selection, timing and amount of N-fertilizer and/or manure applications, timing and type of tillage operations. In addition, flooding, weeds, and scheduled irrigation can be included. Outputs include annual and daily fluxes of C including CO_2, CH_4, DOC, and labile and resistant pools of SOC. Similarly annual and daily fluxes of N, including N_2O, N_2, NO, and NH_3 as well as crop N uptake are outputted. Daily soil temperatures and water-filled pore space are also estimated.

We expended considerable efforts to test and calibrate the DNDC model *versus* experimental data to improve prediction of N_2O emissions from agricultural soils in Canada. Several steps were taken to test and modify the freeze–thaw routine, as well as other basic structures of the DNDC model (Smith et al. 2002). We collaborated with Changsheng Li, one of the authors of DNDC, to ensure that the model was compatible with the extensive environmental and soil conditions that occur across Canada. Modifications were made to the model (DNDC was updated to version 7.2) and further testing for 16 treatments in Saskatchewan and seven in Ontario showed favorable results with 7% average over-prediction in the west and 3% average over-prediction in the east. The variability between measured and predicted emissions was, however, high indicating that the model often over- or under-estimated on a site to site basis, but did well on the average. Our testing exercise, accom-

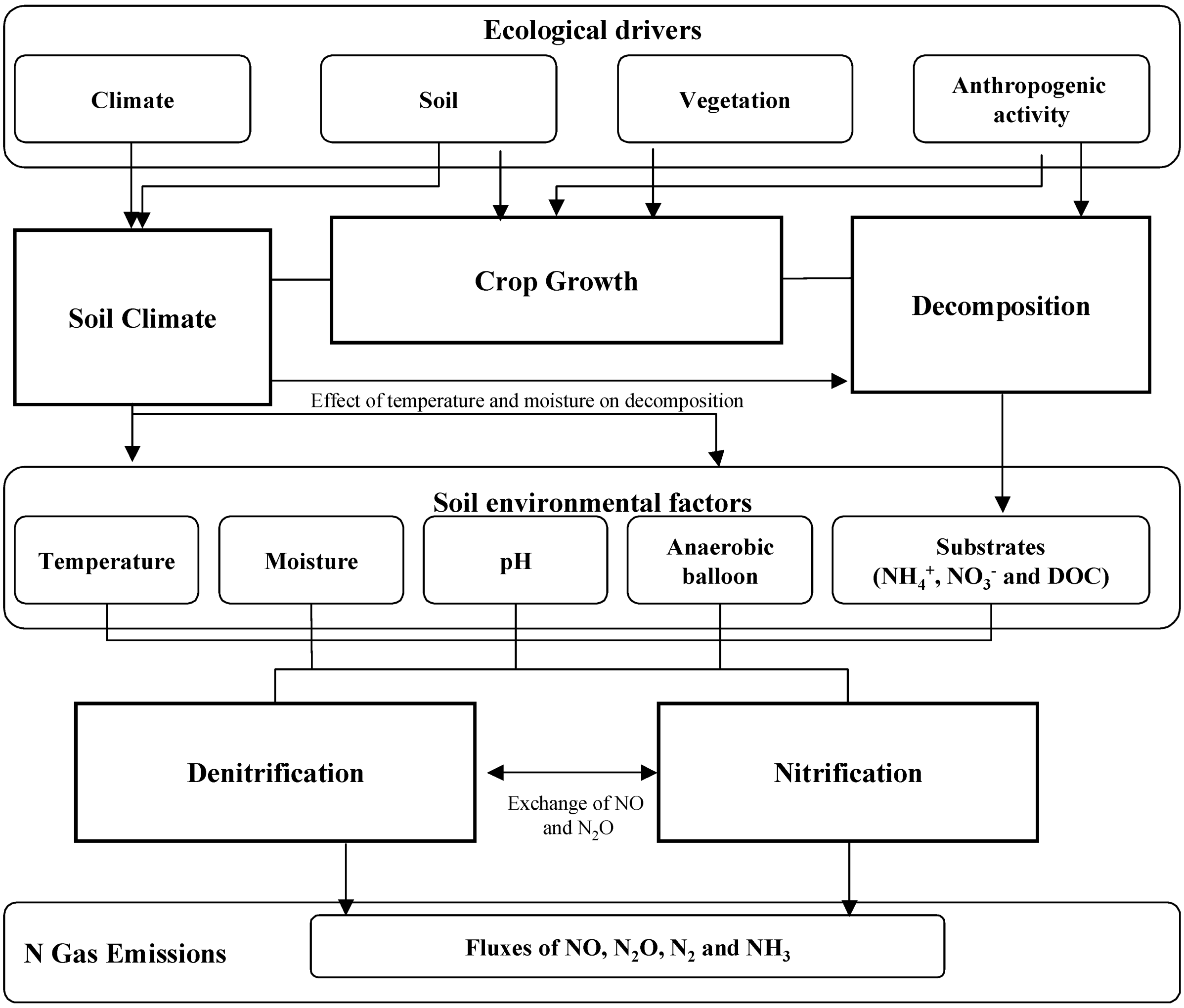

Figure 1. Schematic of the DNDC model.

panied by modification and calibration of DNDC for soils and environmental conditions in Canada provides us with greater confidence in using this model to estimate national N_2O emissions from agricultural soils.

Methodology

The DNDC model was run over a wide variety of agroecosystems across Canada to estimate N_2O emissions at a national level from 1970 to 1999. We have in the past pursued more GIS-like approaches for estimating N_2O emissions across Canada, but such estimates were only made for a couple of years. On a national scale, weather files are often incomplete and even soil data are estimated rather than measured. The aim of our current approach is to run as many scenarios as possible, with a fairly wide range of soil types and soil groups, over a long time period to capture the interannual variations of N_2O emissions. The DNDC model was run for three soil textures (sandy loam, loam, and clay loam) in each of seven soil groups. The soil groups investigated were the Brown Chernozem, Dark Brown Chernozem, Black Chernozem, Dark Gray Chernozem or Luvisol, Gray Brown Luvisol, Gray Luvisol, and Gleysolic. These soil groups represent 80% of the area of cultivated land in Canada. Average soil properties such as bulk density, particle size distribution, pH, and initial organic carbon were calculated from the Soil Landscape of Canada (SLC) polygon database. All simulations were carried out for two to four commonly used crop

Table 1. Crop rotations and fertilizer application rates for all control runs.

Soil group	Rotation	Fertilizer N application rate (kg ha^{-1})
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
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.

rotations in each soil group (Table 1). Some simplification of the crop rotations was necessary to allow for better comparisons across the different soil groups. One crop per year was planted and only major crops were considered. Meteorological data from a representative weather site was chosen for each soil group, one that had near average annual precipitation and temperature within the soil group. Daily temperature and precipitation were input into the model over the 30-year simulation period. Because of the extreme temporal variability in N_2O emissions we found it necessary to simulate emissions over 30 years to capture a full range of estimates.

Current N-fertilizer application rates for each crop rotation were taken from Smith et al. (2000). Fertilizer was applied at 1/3 current rates from 1970 to 1979 and 3/4 from 1980 to 1989, in accordance with Canadian fertilizer consumption (Korol and Girard 1996). In Canada manure is applied to only 7% of the land area and the DNDC model does not currently account for the free NO_3^- and NH_4^+ in manure. The area where manure was applied was thus represented by N-fertilizer addition. Fertilizer, tillage, planting, and harvest scheduling and methods used in DNDC were primarily based on reports by Policy Branch, AAFC (1993–1995) and personal communication with Con Campbell (AAFC). The reports used Agriculture Canada's Regional Agricultural Model (CRAM) and the Erosion Productivity Impact Calculator (EPIC) to predict erosion under various cropping systems.

National estimates were determined by weighting the fraction of crop rotation, soil texture, and soil group, using the following formula:

$$N_{Can} = \sum\nolimits_{j=1}^{g} F_j\left(\sum\nolimits_{k=1}^{t} F_k\left(\sum\nolimits_{l=1}^{r} F_l R_l\right)\right)$$

where N_{Can}=National estimate of N_2O emissions for Canada, g=number of soil groups, F_j=fraction of area covered by soil group, t=number of soil textures, F_k=fraction of area covered by soil texture, r=number of crop rotations, F_l=fraction of area covered by crop rotation, and R_l is N_2O emissions for a particular crop within a soil texture and soil group.

Results and discussion

National estimates

Over the 30-year period from 1970 to 1999 the average annual N_2O emission from agricultural soils in Canada was found to be 39.9 Gg N_2O–N, with a general trend towards increasing N_2O emissions over time (Table 2). The trend corresponds to the increase in N application on agricultural fields (Figure 2). In our simulations, N-fertilizer in Canada was applied at 1/3 current rates from 1970 to 1979 and 3/4 from 1980 to 1989. Average N_2O emissions were estimated to be 28.3 Gg N_2O–N for 1970 to 1979, 44.6 Gg N_2O–N for 1980–1989 and 46.7 Gg N_2O–N for 1990–1999. Variations in rainfall and temperature from year to year are responsible for the high interannual variation in N_2O emissions. Using the IPCC methodology (IPCC/OECD 1996a,b) it was estimated that direct N_2O emissions from agricultural soils in Canada were 37.2 Gg N_2O–N for the year 1996, which is less than the DNDC national estimate of 46.7 Gg N_2O–N for the 1990s. Estimates using IPCC methodology are based on total N-fertilizer used, residues returned to soil, and manure applied. From

Table 2. National and regional N_2O emissions for the years 1970–1999.

Year	N_2O emissions for each Soil Group (kg N_2O–N ha^{-1})							Canada
	A	B	C	D	E	F	U	Gg N_2O–N
1970	0.20	0.49	0.79	0.99	1.12	0.57	1.30	26.8
1971	0.16	0.41	0.79	0.71	0.52	1.08	1.16	23.7
1972	0.21	0.46	0.62	0.66	0.81	0.42	1.15	21.4
1973	0.28	0.54	0.82	1.31	0.67	0.60	2.98	32.3
1974	0.36	0.23	0.54	0.48	0.84	0.63	1.36	20.0
1975	0.46	0.73	0.65	0.56	2.12	1.90	3.45	38.0
1976	0.31	0.50	0.80	0.88	1.28	1.31	2.82	33.3
1977	0.34	0.70	0.99	0.95	1.17	1.01	1.83	33.9
1978	0.35	0.73	0.83	0.76	0.97	0.59	1.44	28.8
1979	0.39	0.31	0.62	0.55	1.38	0.87	1.59	24.8
1980	0.59	0.49	0.95	1.12	3.30	2.28	3.43	47.8
1981	0.62	1.03	1.52	1.82	1.65	1.55	2.41	52.2
1982	0.58	0.42	0.80	1.49	2.27	1.31	2.15	38.0
1983	0.43	0.38	1.17	0.85	2.17	1.08	1.99	37.8
1984	0.59	0.90	1.10	1.48	1.88	0.75	1.95	42.2
1985	0.44	0.95	1.43	1.75	2.88	2.34	4.68	61.0
1986	0.64	1.21	0.70	0.75	2.55	2.55	3.55	46.8
1987	0.79	1.23	0.54	0.85	1.13	0.92	1.65	33.0
1988	0.62	0.88	1.83	1.75	1.54	0.87	1.71	51.1
1989	0.58	0.52	0.64	1.61	2.20	1.54	1.78	36.3
1990	0.70	1.45	1.84	1.70	4.95	2.69	4.24	77.0
1991	0.61	1.05	1.33	1.95	2.98	1.46	2.55	54.8
1992	0.62	0.78	0.55	1.24	2.34	1.19	2.83	38.3
1993	1.23	0.98	0.43	0.55	1.67	0.98	1.91	33.6
1994	0.77	0.73	1.17	2.28	2.67	1.53	2.61	52.1
1995	0.74	0.67	0.67	0.88	3.46	3.73	4.03	50.3
1996	0.72	0.54	0.51	0.80	2.88	1.45	4.45	41.4
1997	0.45	0.68	0.63	0.74	1.34	1.22	1.74	29.6
1998	0.52	0.91	1.31	1.00	2.10	1.56	2.82	47.3
1999	0.75	0.79	0.87	1.69	1.59	1.71	2.46	42.6
kg N_2O–N ha^{-1} y^{-1}	0.54	0.72	0.92	1.14	1.95	1.39	2.47	
Gg N_2O–N	2.82	4.97	11.69	4.62	6.25	2.92	6.60	39.9

A, Brown Chernozemic; B, Dark Brown Chernozemic; C, Black Chernozemic; D, Dark Gray Chernozemic/Luvisolic; E, Gray Brown Luvisolic; F, Gray Luvisolic; U, Gleysolic.

1990 to 1999, IPCC estimates of direct N_2O emissions from agricultural soils will change little from year to year, slightly increasing each year with the animal population and the amount of N-fertilizer applied. Estimates from the DNDC model simulations were found to vary substantially from year to year, due to interannual variations in the amount of rainfall, temperature, and most importantly the timing of rainfall events, and conditions during spring thaw. Total DNDC model emissions estimates in Canada from 1990 to 1999 ranged from 29.6 to 77.0 Gg N_2O–N.

Regional estimates

As expected, predicted emissions of N_2O were greater in wetter and more intensively cropped soils. Over the 30-year period, the Gleysolic soil had the largest average annual emissions of 2.47 kg N_2O–N ha^{-1} y^{-1}. Much of this soil group is located in southern Ontario. Estimated annual emissions of N_2O in the dryer western soil groups, Brown, Dark Brown, and Black Chernozems, were 0.54, 0.72, and 0.92 kg N_2O–N ha^{-1} y^{-1}, respectively. The largest total emissions occurred in the Black Chernozem (11.69 Gg N_2O–N y^{-1}) due to the large land area that soil group covers. Measured emissions of N_2O from nine treatments near Elora, Ontario, ranged from 0.3 to 7.4 kg N_2O–N ha^{-1} y^{-1} with a weighted average of 2.8 kg N_2O–N

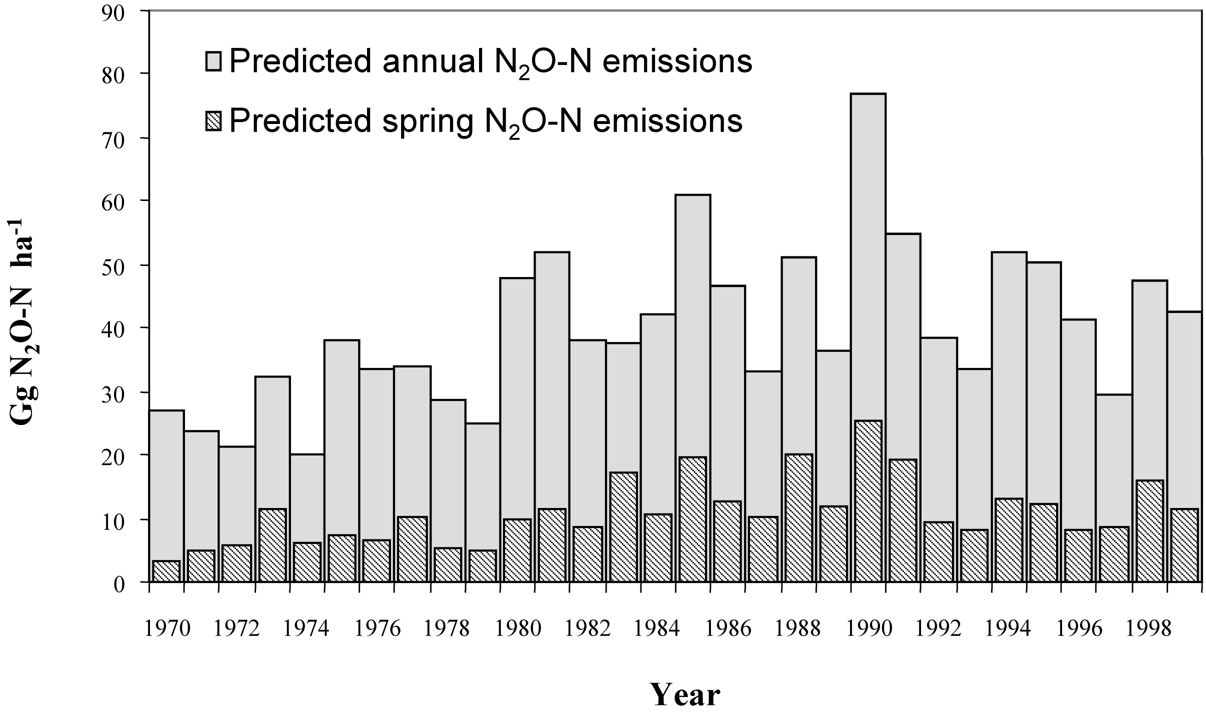

Figure 2. Estimated direct emissions of N_2O from agricultural soils in Canada from 1970 to 1999.

ha^{-1} y^{-1} (Wagner-Riddle et al. 1996). The nine treatments covered a wide variety of crops and management practices in Ontario. The average emissions correspond quite closely to our estimated emissions from the Gleysolic soil group. Emissions from 10 western treatments (shoulder and footslope landform) near St. Louis, Saskatchewan, a dry area, ranged from 0 to 3.4 kg N_2O–N ha^{-1} y^{-1} with an average of 0.5 kg N_2O–N ha^{-1} y^{-1} (Corre et al. 1996). Large variations in measured N_2O emissions occurred primarily because of variations in landform. The annual N_2O emissions from the footslope land formation at an alfalfa site in St. Louis, Saskatchewan was 0.006 kg N_2O–N ha^{-1}, whereas Kroeze et al. (1995) suggested that an emission of 4 kg N_2O–N ha^{-1} y^{-1} should be used as a general emission rate for legumes. We estimated using DNDC that emissions of N_2O in eastern Canada (Atlantic Provinces, Quebec, Ontario) were about 36% of the total emissions in Canada, though the cropped area is only 19% of the total.

Our analysis was carried out by averaging soil properties and obtaining representative meteorological conditions for each soil group. The temporal variability of N_2O emissions for each major soil group is then accounted for while the spatial variability of soil properties and weather is not. The previous study estimated total emissions in Canada to be 39.4 Gg N_2O–N ha^{-1} whereas our current study shows 52.1 Gg N_2O–N ha^{-1}. The more recent version of DNDC estimates 20–43% more emissions during spring thaw, depending on soil groups, than did the previous version. This accounts for most of the discrepancy in results between the two methodologies. Note that when the model was run on a soil landscape of Canada polygon basis we still had to use average soil properties on a 1:1 000 000 scale from the dominant soil within the polygon and weather data from the closest station that had a near complete set of data. We believe that the current study provides a good average estimate of greenhouse gas emissions for the major soil groups, crop rotations and soil textures within Canada.

Emissions during spring thaw

In the more recent version of DNDC the physical–chemical processes have been modified to include freezing and thawing and snow insulation. On average, over the seven soil groups, N_2O emissions during spring thaw were about 30% of total yearly emissions. N_2O emissions during the growing season accounted for about 55% of yearly emissions. Both

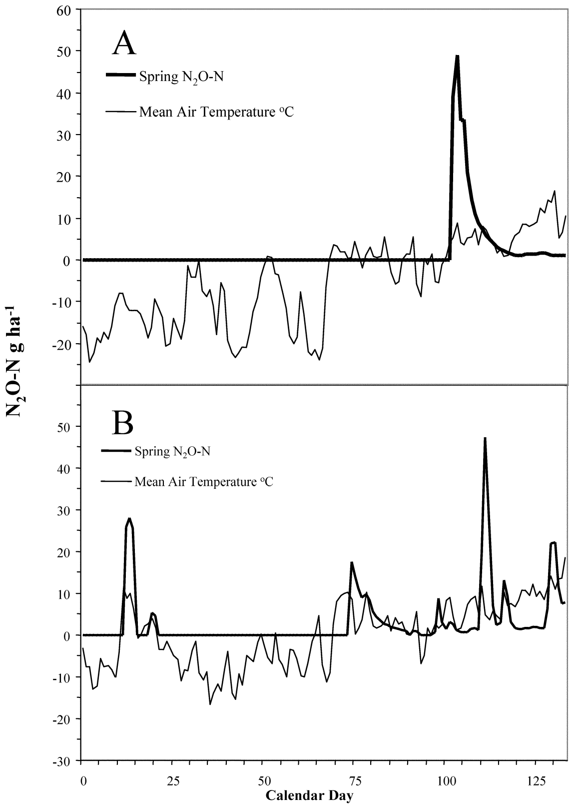

Figure 3. Predicted spring N_2O emissions for: (A) loam textured soil in the Dark Brown Chernozem; wheat–fallow rotation in 1995; and (B) loam textured soil in the Gray Brown Luvisol; corn–corn–barley–barley rotation in 1995.

Teepe et al. (2000) and Kaiser et al. (1998) found that during the winter period approximately 50% of the total annual N_2O emissions were observed. This compares well with the 48% of the total N_2O emissions that we simulated over the winter period with DNDC (December–April).

Many studies have found that N_2O flux is highest in the spring (Goodroad and Keeney 1984; Parsons et al. 1991; Groffman et al. 1993; Burton and Beauchamp 1994). Higher denitrification can occur due to higher moisture contents as a result of snowmelt. Also, more nitrogen may be available due to low plant activity. Furthermore, high N_2O emissions may result from changes in solubility and N_2O that has accumulated under a frozen soil layer and then later diffuse upon snowmelt and thawing (Goodroad and Keeney 1984; Burton and Beauchamp 1994). In the DNDC model spring thaw events are temperature dependent. Spring thaw can result in emissions of N_2O occurring as one short burst (Figure 3A) or as several bursts (Figure 3B), depending on temperature conditions. Version 7.2 of the DNDC model assumes that N_2O production from denitrification, as a result of microbial activity, is trapped by a physical boundary of ice and is released during soil thawing. As well a small portion of simulated spring burst in DNDC can be attributed to the N accumulation in the snow pack over the winter months. While many researchers agree that this physical boundary of ice prevents the escape of nitrous oxide into the atmosphere, the exact processes of the generation of this N_2O in soil during the winter months are still not fully understood. There is evidence that at least a portion of the N_2O released during or just following spring thaw is currently biologically active. Until more research is available it is difficult to assess whether the DNDC model encompasses the full range of processes that are responsible for the N_2O fluxes generated during spring melt.

Interannual variations in temperature and rainfall

Variations in air temperatures and rainfall can have a significant impact on N_2O emissions. The denitrification submodel in DNDC operates on an hourly timestep and is activated with freezing temperatures, when soil moisture increases, and/or soil oxygen availability decreases. Large rainfall events of long duration can dramatically increase N_2O emissions, causing more emissions in certain years, even if the total yearly rainfall is close to the yearly average. It was estimated that the largest emissions of N_2O in Canada occurred in 1990 (Figure 2), a year with average total precipitation. It appears to be more the timing of the rainfall and the increased frequency of freeze thaw events that resulted in increased estimated emissions during this year. Unusually high N_2O emissions during the year 1990 have considerable implications for a country as far as meeting its Kyoto commitment. This fact clearly demonstrates the problem that can arise by using a baseline estimate that focuses on only one year. Other researchers have also found that climate can significantly influence interannual soil carbon change and greenhouse gas emissions (Griffis and Rouse 2001; Flanagan et al. 2002).

Part of the overall increase in N_2O emissions from 1970 to 1999 may result from a slight increase in air temperature. A regression over the past 30 years, weighted across the seven soil groups, shows an increase in maximum temperatures of 0.8 °C and an increase in minimum temperatures of 1.0 °C. Thus, the weather data selected for this project indicate a temperature increase of 0.9 °C in Canada. Fluctuations in temperature during the year can have an influence on annual N_2O emissions, especially during spring thaw (Figure 3); however, it is questionable whether or not a 0.9 °C increase in temperature would make any significant difference in emissions. Increases in temperature can result in more thaw periods accompanied by more emission events. The microbial activity and organic matter decomposition may also be influenced, as well as the soil–water content.

Summary and conclusions

Direct N_2O emissions were estimated from agricultural soils in Canada for the period between 1970 and 1999. The DNDC model was run over a wide variety of agroecosystems, three soil textures and two to five crop rotations in each of seven major soil groups. Over the 30-year period, the average N_2O emissions from agricultural soils in Canada were found to be 39.9 Gg N_2O–N, with a general trend towards increasing N_2O emissions over time. The average emissions over the last 10 years were 46.7 Gg N_2O–N. The trend is primarily a result of increased application of N-fertilizer. About 30% of the N_2O emissions in Canada occurred during spring thaw events and the greatest N_2O emissions occurred in the wetter, more intensively cropped eastern soils. The high interannual variations in the estimated N_2O emissions resulted from variations in temperature and rainfall, with the length and intensity of rainfall events being of primary importance towards increased N_2O emissions. Our emission estimates compared well with average estimates from experimental sites, and the average national estimates from 1990 to 1999 compared well with 1996 IPCC estimates.

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