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A tool to link agricultural activity data with the DNDC model to estimate GHG emission factors in Canada

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ABSTRACT

Research is ongoing to develop ways to reduce emissions of greenhouse gases (GHGs) from agricultural sources. A convenient technique to estimate emissions is to develop emission factors for a wide range of management practices. Default emission factors such as those given in the Intergovernmental Panel on Climate Change Tier I methodology are often used but these can result in substantial errors when applied to specific geographical regions. In this paper an interface was developed to link soil, climate and agricultural activity data in Canada with the DeNitrification and DeComposition (DNDC) model to create a modeling tool for estimating emission factors for changes in agricultural management. This tool was also designed to calculate country-specific IPCC Tier II emission factors for comparison against modeled results. The DNDC-Management Factor Tool (DNDC-MFT) was developed to automatically generate soil, climate and agricultural management model input data from national databases for estimating emissions factors for any of 462 ecodistricts across Canada. Six ecodistricts were selected across the major climatic regions to test the tool. The emission factors generated by the DNDC model were significantly different from Tier II values. Much variability in N_2O emission estimates exist, partly due to limitations in certain biophysical processes in the model and partly due to quality of input data. The DNDC model is very sensitive to climate, size of initial soil C levels, and fertilizer application rates. We should also keep in mind that there is uncertainly associated with Tier II emission factors. The combined N_2O and soil C factors estimated by the DNDC model are generally comparable to values that are being used to estimate Canada's national inventory (Tier II/III) but only the tillage factor was found to be statistically similar. The DNDC-MFT will be useful for testing the ability of the DNDC model to generate GHG emission factors for many management scenarios across varying climatic regions in Canada. The framework can be extended to include improved versions of DNDC and other ecosystem models.

1. Introduction

In 2006, greenhouse gas (GHG) emissions from agricultural production excluding fossil fuel use amounted to approximately 8% of Canada's overall GHG emissions. Agricultural activities in Canada are a significant and increasing source of both nitrous oxide (N_2O) and methane (CH_4) emissions, whereas Canadian agricultural soils are approximately neutral with respect to carbon dioxide (CO_2) emissions (Smith et al., 2000). Since 1990, growth in the beef, pork and poultry industries, as well as increased use of synthetic N fertilizers have caused an increase in N_2O and CH_4 emissions, whereas the adoption of beneficial management practices (BMPs), especially in the semi-arid to sub-humid prairie region has decreased national soil CO_2 emissions (McConkey et al., 2007). There is a growing need to develop GHG mitigation techniques for all sectors of the economy to minimize the risk of undesirable climate modification and to meet agreed upon emissions reduction targets. Several agricultural management practices have been shown to reduce GHG emissions, however the challenge facing the agricultural sector is to reduce net emissions while increasing production to meet the growing demand for food, fibre and biofuel.

Greenhouse gas emissions are highly variable hence it is difficult to integrate emissions over space and time. It is then important to develop methodologies to estimate and predict GHG emissions from agricultural systems under contrasting environments particularly since changes in climate can affect the mitigation potential of a practice. The Intergovernmental Panel on Climate Change (IPCC, 2006) has developed procedures for estimating changes in GHG emissions however the recommended

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default, or Tier I, emission factors are very general and can result in substantial errors under certain conditions. Some countries have developed Tier II emission factors for agricultural systems, which are based on country-specific measurements and thus provide more accurate emission estimates. However, because the Tier II emission factors were developed under certain climatic conditions, they may not apply for climate change projections.

Process-based models can be used to predict the impact of various agricultural management practices on net GHG emissions by analysing the interactions between management practices, primary drivers (climate, soil type, crop type, etc.), and biogeochemical reactions. Because process models take into account the interrelationships between various input factors, a level of analysis is possible beyond that which could be performed using empirical emission factors alone.

There has been much progress in recent years in developing models which can simultaneously simulate the interactions between soil carbon and trace gas emissions of N_2O and CH_4. This is important because it is not uncommon for emissions of one GHG to increase while the emissions from another decline as the result of an imposed change in agricultural management, making it essential to consider combined emissions, rather than any one gas in isolation. The DeNitrification and DeComposition (DNDC) (Li, 2000) and Daycent (Del Grosso et al., 2001) models have been used extensively to predict GHG emissions over space and time for a wide range soils, farm management and climatic conditions in several countries around the world (Del Grosso et al., 2006, 2009; Leip et al., 2008; Saggar et al., 2007), and have also been used to estimate GHG emission factors for changes in land management (Smith and Bertaglia 2007; Grant et al., 2004; Desjardins et al., 2004). Using a combination of empirical data and estimates from the DNDC and Daycent models, Smith and Bertaglia (2007) derived emission factors for changes in agricultural management for major climatic regions around the world and estimated a global mitigation potential by 2030 of approximately 6000 Tg CO_2 eq. y^{-1}.

Process-based models are improving as gaps in knowledge are addressed; however, most models are still limited in accuracy. It is important to acknowledge and address model limitations to lower uncertainties in the estimates. Models can provide a cost effective means to estimate GHG emissions over space and time under a wide range of agricultural management and are useful tools for scaling up site specific information to regional estimates. The objectives of this work are the following: (1) to develop an interface to link Canadian soil and climate databases with the DNDC model for estimating carbon dynamics and N_2O emissions from agricultural soils in Canada, (2) to estimate DNDC model derived emission factors for major changes in agricultural management for selected ecodistricts in Canada, and (3) to compare the model outputs with Tier II country-specific emission factors. The DNDC-Management Factor Tool (DNDC-MFT) is designed to allow for the incorporation of new versions of the DNDC model and it could be adapted to include other models.

2. Methodology

2.1. DNDC model

The DNDC model (Version 9.3) is a process-based soil biogeochemical research tool that was developed to estimate the impact of management strategies on the fate of nitrogen (N) and carbon (C) in agroecosystems. It integrates crop growth processes with soil biogeochemical processes on a daily time step and simulates important processes related to N and C cycles in plant–soil systems, including mineralization, ammonia volatilization, nitrification, denitrification, N uptake, and leaching. To track the impacts of cropping practices on N and C cycling, DNDC includes detailed algorithms to quantify the effects of crop rotation, tillage, fertilization, irrigation, manure amendments, weeding, and grazing. The model has been validated across the world and has been used for many sub-national and national greenhouse gas inventories. In Canada, the DNDC model has been used to estimate N_2O emissions in comparison to measurements from experimental sites (Smith et al., 2002, 2008), to estimate interannual variations in emissions at a national level (Smith et al., 2004), and has been used to estimate N_2O emission factors for changes in agricultural management (Grant et al., 2004). This research has led to significant improvements in DNDC's ability to model C and N fluxes in cold climate regions which have been incorporated into DNDC Version 9.3. An additional improvement has been added to the model for this project, as it was found that the model predicted the same soil–water characteristics regardless of residue cover. Thus the function as described in Steiner (1989) was added to the DNDC model to improve estimates of soil evaporation under different levels of surface residue cover.

2.2. Database construction

The national database at the ecodistrict level was utilized to facilitate model simulations. Ecodistricts are the most spatially detailed level of information available within Canada's National Ecological Framework, and have been adopted as the base modeling unit in this project. The DNDC model requires input datasets pertaining to soil characteristics, daily climate, and agronomic management. To construct a national DNDC input database at the ecodistrict level for all of Canada, the individual input datasets were obtained from various sources in different formats and levels of spatial detail. The following sections detail the data sources as well as the methods to process the data at the ecodistrict level.

2.3. Soil inputs

Soil data were obtained from Version 3.1 of the Soil Landscapes of Canada (SLC) database (Agriculture and Agri-Food Canada, 2006). The soil database includes a means to extract data at the ecodistrict level. DNDC input values (0–5 cm depth) were obtained from the A horizon of mineral soil for the following variables: % sand, % silt, % clay, soil organic carbon (SOC), pH, bulk density, hydraulic conductivity, saturation, field capacity, and wilting point. Occasionally the Canadian soils database has entries for only native sites with an organic layer of partly decomposed forage/tree litter. In such cases the A horizon was taken as the surface layer and the forage/tree residue layer was removed. The DNDC model only accepts soil inputs from one soil surface layer and the A horizon should better characterize an agricultural soil. Note that 10 years of spin up simulation was carried out to stabilize soil C before emission factors were estimated. Soil layers that contained missing data (<5%) for any of the DNDC variables were removed from the calculation of DNDC input values. The DNDC-MFT was designed with options to either run the dominant soil in the ecodistrict or run the tool for three base textures; coarse, medium, or fine. Soil data were separated into these textural classes based on the SLC database 'Parent Material Texture' field and average soil properties were estimated for each of the three classes. Note that the user of the interface can also redefine any soil property used in the simulations.

2.4. Climate inputs

Climate inputs required by DNDC include daily air temperature (minimum and maximum), precipitation, and solar radiation.

These inputs were derived from an ecodistrict level dataset that contained historical records from 1951 to 2004 (interpolation of observed values within ecodistrict) and extrapolated values from 2005 to 2020. A number of ecodistricts, primarily in the areas of marginal agricultural land, were missing climate data. Missing climate data fell into one of three categories: certain variables missing for entire year, all variables missing for entire year, and sporadic periods of missing data throughout the year. Any instances of missing data had to be corrected to ensure that a complete set of climate inputs existed to perform long-term (1951–2020) DNDC simulations for any agricultural ecodistrict. The method used to correct the climate records was dependant on a number of factors: (a) the length of time that data were missing, (b) the availability of data from a neighbouring ecodistrict, and (c) the climate variable that was being corrected (temperature, precipitation, radiation). A gap-filling algorithm was used to interpolate temperature and radiation values for sporadic periods that did not exceed one day of missing data. An average of the previous and following day's temperature and radiation values were assigned. Data from the nearest neighbouring ecodistrict (within 250 km) that contained climate data were assigned in instances where data were missing either for the entire year or for sporadic periods of more than one consecutive day. If no neighbouring ecodistrict within 250 km contained climate data, the long-term average temperature and radiation was assigned (as determined from an average of all years where data existed for that ecodistrict). To fill in missing precipitation data values from the nearest neighbouring ecodistrict (within 250 km) that contained precipitation data was assigned. If no neighbouring ecodistrict within 250 km contained precipitation data, a randomly-selected year of existing precipitation data from that ecodistrict was used.

2.5. Agricultural activity data

Crop rotation data were obtained from two sources. For the Prairie Provinces, rotation data were obtained from a dataset generated by the Prairie Farm Rehabilitation Administration (PFRA). For the remainder of the country, rotations were assigned based on a previous analyses by Smith et al. (2000). These datasets were provided at the SLC Version 2 level of detail, which have different polygons than the SLC Version 3.1 used in this project. The GIS analyses used to determine the rotations for each ecodistrict (Prairie and non-Prairie Provinces) are described as follows. From the PFRA district map a polygon map was created then georectified using control points from a provincial boundary map of Canada. Using GIS overlay techniques it was determined which PFRA district represented the majority of each ecodistrict. Crop rotations from this PFRA district were assigned to an ecodistrict. For eastern Canada a Version 2 polygon map was overlaid with an ecodistrict map and rotations were assigned to ecodistricts using a nearing neighbour algorithm. Approximately 125 individual rotations were assigned across Canada with 1–13 rotations assigned to each ecodistrict. Crops simulated included alfalfa, canola, corn (grain), corn (silage), flax, barely, oats, rye, non-legume hay, pasture, potato, pulses, soybean, summer-fallow, wheat (spring), and wheat (winter).

Default planting, harvest, and tillage scheduling were derived from work by Smith et al. (2000). For hay and alfalfa the number of cut events was based on expert opinion, with western Provinces having one cut (June 20) and eastern Provinces having two cuts (June 20, August 1). The amount of biomass cut is an input variable required by DNDC and 85% of above ground biomass was cut (removed) as the default for all dates. In eastern Canada the default conventional till consisted of mouldboard ploughing in the spring before planting and in the fall after harvest. In western Canada a ploughing depth of 10 cm was assumed. This methodology is consistent with Canada's National Carbon and Greenhouse Gas Accounting System (McConkey et al., 2007).

Fertilizer was applied at time of planting and application rates were based on an interim product of the work reported in Huffman et al. (2008). Note that a reduced rate of fertilizer was applied after summer-fallow assuming N was generated from mineralization during the fallow year. A small amount of starter fertilizer was applied to soybean and pulse crops during planting. All fertilizer N applications were applied as nitrate additions using a surface broadcast application technique.

2.6. Development of DNDC-MFT

The DNDC-MFT allows users to select and run the model for any ecodistrict within Canada (Fig. 1). A user-friendly version of the tool will soon be made available to researchers upon request. The main program for DNDC-MFT was developed in Visual Basic from within Microsoft Excel and the GIS information from the databases was imported into Excel for easy access. The user can select factors for changes in management they wish to determine or the program can simulate a combined factor for a combination of management changes. Input files for DNDC are created for baseline and factor

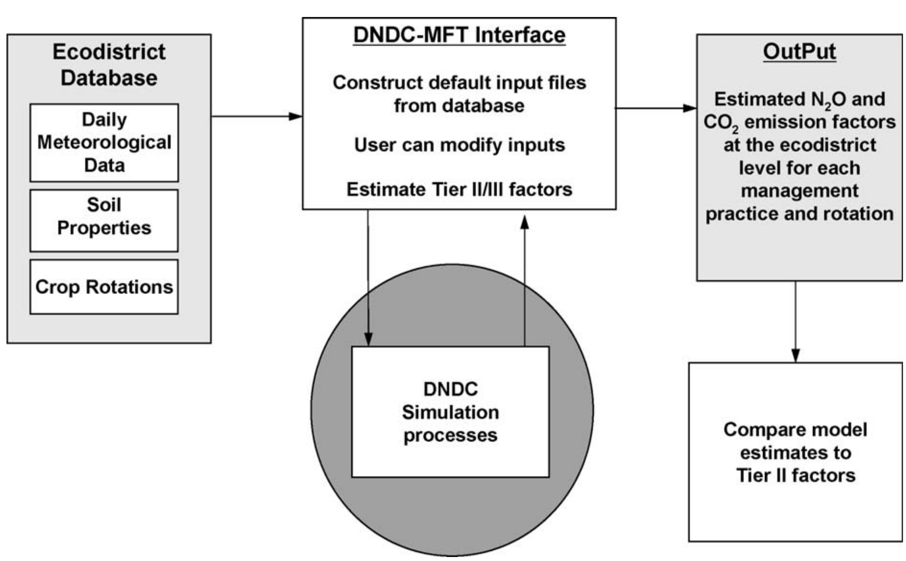

Fig. 1. Schematic of the system to develop and test GHG emission factors across Canada as a function of management practices.

simulations automatically from the ecodistrict database. The user has the capability to modify several soil and activity data before DNDC input files are created.

The sequence of events in estimating emission factors is as follows: an ecodistrict is selected, the types of factors to be generated are selected, necessary data sources are retrieved, input files are constructed for the DNDC model, simulations are automatically carried out, both model-based and Tier II emission factors are calculated then results are reported in tables.

2.7. Estimating soil C and N_2O factors

The DNDC-MFT works primarily like a GHG calculator to estimate emissions at the ecodistrict level. On a personal computer it could take weeks for running the tool to estimate emission factors for all ecodistricts in Canada. It is intended that the interface be used for estimating factors for areas of interest and in doing so the user is free to change the base inputs the interface retrieves from the database before simulations are complete.

In this paper we test the functionality of the DNDC-MFT interface and provide examples for the output of the program for four changes in agricultural management in two sub-arid, two sub-humid and two humid ecodistricts (Table 1). The DNDC-MFT interface automatically reads in base soils, agricultural management and daily climate for the selected ecodistrict. For this example we used dominant soil texture for each ecodistrict, however, the user can run the tool for fine, medium and coarse textures within each ecodistrict or input their own soil properties if desired. To estimate factors within the framework baseline management is first simulated from 1970 to 2020 for each rotation within the ecodistrict then changes in management are applied and further simulations are performed. Simulations for changes in management are carried out by running default rotations from 1970 to 1979, to allow the DNDC model to stabilize, followed by the change in management from 1980 to 2020. The following management changes were included; conversion of conventional till (CT) to no till (NT), removal of summer-fallow, zero fertilizer, and conversion of cropland to permanent cover. Note that any combination of these changes in management practices can also be selected to determine a combined factor.

Nitrous oxide emission factors were estimated by averaging emissions for the 20-year period following changes in agricultural management and then these values were subtracted from baseline estimates. Soil C factors were estimated by taking the slope of regressions of soil C stocks (0–20 cm depth) for 20 years following a change in management. This depth coincides with previous Tier II/III estimates from Canada's National Carbon and Greenhouse Gas and Accounting and Verification System. Values were subtracted from baseline slopes and adjusted for the number of occurrences of the management change in the rotation. For example, if fallow was eliminated from a 2-year wheat-fallow rotation the resulting change in carbon would be multiplied by two to determine a fallow factor. Thus the values in the result tables always represent a complete change in the management for a year.

2.8. Tier II emission factors

The Tier I methodology for estimating national inventories of agricultural soil N_2O emissions developed by the IPCC (2006), recommends a default N_2O emission factor of 0.01 kg N_2O-N kg^{-1} N. This is close to the experimentally derived average growing season emission factor for eastern Canada of 0.012 kg N_2O-N kg^{-1} N (Gregorich et al., 2005). However, the IPCC default emission factor overestimates emissions in western Canada which accounts for approximately 80% of agricultural production in Canada, where N_2O emission factors have been found to be 4–10 times less than in eastern Canada (Rochette et al., 2008a) and underestimates emissions in eastern Canada, when emissions during spring thaw are considered (Wagner-Riddle et al., 2007).

To address the shortcomings of the IPCC Tier I N_2O emission factor, an empirical country-specific or IPCC Tier II methodology was developed to estimate Canadian agricultural soil N_2O emissions for international reporting (Rochette et al., 2008a). This methodology estimates a 'base' N_2O emission factor at the ecodistrict spatial scale from experimental results as a function of the growing season (May–October) ratio of precipitation to potential evapotranspiration (P/PE) as:

$$EF_{\text{base}} = 0.022\frac{P}{PE} - 0.0048 \tag{1}$$

The minimum P/PE was 0.29, where EF_{base} = 0.0016 kg N_2O-N kg^{-1} N and the maximum P/PE was set at 1, where EF_{base} = 0.017 kg N_2O-N kg^{-1} N. The base emission factor can be modified for management practices such as tillage and irrigation, as well as landscape position and soil texture, which can influence water availability and N_2O emissions (Rochette et al., 2008a). For the purpose of this study, the effect of landscape position was ignored, because fields were assumed to be located in the midslope position, which is not subjected to repeated wetting and drying cycles. The effective ecodistrict scale N_2O emission factor (EF_{eff}) is then calculated as:

$$EF_{\text{eff}} = EF_{\text{base}} \times F_{\text{text}} \times F_{\text{till}} \tag{2}$$

where F_{text} = texture ratio factor; F_{till} = tillage ratio factor and

$$F_{\text{text}} = \frac{A_c}{A_T} \times 0.8 + \frac{A_m}{A_T} \times 1.0 + \frac{A_f}{A_T} \times 1.2 \tag{3}$$

where A_c = the area of coarse textured soils in an ecodistrict; A_m = the area of medium textured soils in an ecodistrict; A_f = the area of fine textured soils in an ecodistrict; A_T = total area of agricultural soils in an ecodistrict.

In western Canada, F_{text} equals 1. Following Rochette et al. (2008a), in eastern Canada, F_{till} was set at 1.1 for NT and reduced tillage and 1.0 for CT and in western Canada F_{till} was set at 0.8 for NT and reduced tillage and 1.0 for CT. For irrigated soils, P/PE = 1, where EF_{base} = 0.017 kg N_2O-N kg^{-1} N.

Table 1
Properties of selected ecodistricts for testing DNDC-MFT.

Ecodistrict number	Province	Great group	Climatic region	Soil texture	SOC (%)	BD (g cm^{-3})	pH	Annual precip (cm)
559	Ontario	Melanic Brunisol	Humid	Silty clay loam	3.90	1.10	6.4	83
546	Quebec	Melanic Brunisol	Humid	Sandy silt loam	2.56	1.20	7.1	98
760	Saskatchewan	Black Chernozem	Sub-humid	Clay loam	2.25	1.29	7.1	47
727	Alberta	Black Chernozem	Sub-humid	Clay loam	3.97	1.19	5.5	48
825	Saskatchewan	Dark Brown Chernozem	Semi-arid	Clay loam	2.08	1.32	6.8	37
819	Saskatchewan	Brown Chernozem	Semi-arid	Loamy sand	1.10	1.39	6.5	33

2.9. Soil carbon change factors

Tier II/III soil C change factors (0–20 cm depth) for changes in management were obtained from the National Carbon and Greenhouse Gas Accounting and Verification System (McConkey et al., 2007). Carbon factors for changes in tillage and permanent cover management were derived from Century model estimates (Tier III) whereas factors for elimination of fallow were derived from empirical estimates (Tier II). Results were estimated at the Soil Landscape of Canada (SLC) polygon soil unit then were scaled up to the ecodistrict level.

3. Results and discussion

3.1. DNDC-MFT

The DNDC model was successfully linked to soils, daily climate and agricultural activity data for 462 ecodistricts across Canada. The ecodistricts encompass almost all of the agricultural land area in the country. The DNDC-MFT is capable of constructing input files from the GIS database for DNDC and simulating soil C dynamics and direct N_2O emissions for a range of agricultural management practices for several crop rotations within any selected ecodistrict. Indirect emissions can be estimated using emission factors from Tier II methodology, however, the DNDC model does not quantify indirect N_2O emissions from leaching, runoff, and volatilization. To assess the quality of the output from this tool emission factors were generated for four changes in agricultural in two semi-arid, two sub-humid and two humid ecodistricts. Within the DNDC-MFT framework simulations were carried out and Tier II factors were estimated for rotations within each ecodistrict and results are presented in Tables 2–4 showing a breakdown of factors generated for N_2O-N emissions, soil C change, and total combined emissions by rotation within each ecodistrict.

3.2. N_2O emissions

Estimated baseline emissions of N_2O using the DNDC model for default crop rotations were generally higher than were Tier II estimates (Table 2). Since Tier II estimates are primarily based on measurements (Rochette et al., 2008a) this indicates that the current version of the DNDC model may be overestimating N_2O emissions, at least for these specific ecodistricts. Both the base emissions and the emission factors as predicted by the DNDC model were found to be significantly different from Tier II estimates. This is not surprising considering that N_2O emissions are highly variable and that there are errors associated with both modeled and Tier II emission factors. As expected, N_2O emissions are relatively low in semi-arid and sub-humid regions in comparison with humid regions. Under conversion from CT to NT agriculture both the DNDC model and Tier II methodologies predict a reduction in N_2O emissions in western semi-arid and sub-humid soils. The DNDC model predicted little change in emissions for NT in eastern humid soils whereas Tier II showed an increase in emissions of 0.24 kg N_2O-N ha^{-1} y^{-1}. Experimental evidence indicates that in semi-arid and sub-humid regions of western Canada N_2O are generally reduced under NT (Helgason et al., 2005) whereas, on the average, they increase in humid regions of eastern Canada (Rochette et al., 2008a). As Tier II methodology is based on these assumptions it also produces results that are in line with these findings. Experimental results can, however, be highly variable. At an experimental site in eastern Canada, Rochette et al. (2008b) found that NT more than doubled N_2O emissions in a heavy clay soil but emissions were similar between NT and mouldboard ploughing in a loam soil. The extreme level of emission (12–45 kg N_2O-N ha^{-1}) from the heavy clay soil was attributed to high rates of denitrification due to high water content, reduced aeration and decomposition of large amount of organic matter stocks. For our example run of DNDC-MFT we did not simulate a full range of soils and only generated factors for a sandy silt loam and a silty clay loam in humid ecodistricts. One reason why DNDC may be underestimating emissions in NT systems is that the model does not significantly increase soil–water under NT. The Steiner equation was incorporated into the model to reduce evaporation under heavy surface residue which resulted in lowering evaporative losses by 25%. However, as a result of this change, more evapotranspiration and leaching occurred and simulations end up with approximately the same net water loss from the system. The moisture model is driven by a tipping bucket routine and excess water above field capacity tends to drain quickly.

The DNDC model on average predicted increased N_2O emissions when fallow was eliminated. More N_2O emissions generally occur under continuous cropping though the factors are variable across ecodistricts and rotations. Note that for certain rotations such as the barley–summer-fallow–spring wheat rotation in ecodistrict 825 the emission factor was very high at 2.36 kg N_2O-N ha^{-1} y^{-1}. The fertilizer rate of 58 kg N ha^{-1} for barley that was extracted from the database may have been too high for this dry location (37 cm annual average precipitation). The DNDC model predicted that excess N, that was readily available for nitrification and denitrification, remained near the soil surface. The Tier II methodology assumes that emissions from fallow are the same as from annual crops thus the factor was 0.

Emission factors were estimated for complete removal of fertilizer. This was carried out to determine the contribution of fertilizer to the N_2O budget. According to the DNDC model applied fertilizer accounted for over 75% of the emissions across the three climatic regions. Estimates using Tier II methodology indicated that the contribution of fertilizer to emissions was lower with a large portion of emissions derived from crop residues. Under a permanent cover scenario with unimproved grassland (no fertilizer N addition) both the DNDC model and Tier II methodology predicted almost a complete reduction in N_2O emission.

3.3. Soil carbon change factors

Estimates of C change factors for conversion of conventional till to no till using the DNDC model for semi-arid, sub-humid, and humid soils were −0.06, −0.12 and −0.05 Mg C ha^{-1} y^{-1} respectively (Table 3). Estimates from Tier II/III methodology were −0.10, −0.15 and −0.09 Mg C ha^{-1} y^{-1} respectively. Using a *t*-test it was determined that emission factors estimated by DNDC were significantly different from Tier II/III factors, however both techniques have error associated with their estimates and it is difficult to say which are more accurate. In a summary of empirically derived CT to NT factors. VandenBygaart et al. (2008) found that average factors were −0.09 Mg C ha^{-1} y^{-1} across five studies in semi-arid prairies, −0.22 Mg C ha^{-1} y^{-1} for 8 experiments in sub-humid prairies, and averaged −0.06 Mg C ha^{-1} y^{-1} for three sites in eastern Canada (Quebec and Ontario). The reliability of these values was low with just one standard deviation being greater than the average factors. The effect that tillage has on soil C is highly variable and depends on soil type and climate. A number of experiments now indicate that no change or a loss in soil C can sometimes occur when converting from CT to NT. The effect of tillage on the rate of soil C decomposition is dependent on soil texture, climate and the type of tillage practice, and lately considerable attention has been given to buried carbon whereby the decomposition rate in the lower profiles of conventionally tilled soils can be low. Christopher et al. (2009) found that in 8 of 12 major land resource areas across three

Table 2
Estimated N_2O-N emission factors for changes in agricultural management calculated over 20 years. Emission factors for the management scenarios are relative to the base emission case.

Ecodistrict number	Rotation	DNDC estimated					Tier II estimated				
		Base emission ($kg\,ha^{-1}\,y^{-1}$)	CT to NT ($kg\,ha^{-1}\,y^{-1}$)	Eliminated Sf ($kg\,ha^{-1}\,y^{-1}$)	No fertilizer ($kg\,ha^{-1}\,y^{-1}$)	Permanent cover ($kg\,ha^{-1}\,y^{-1}$)	Base emission ($kg\,ha^{-1}\,y^{-1}$)	CT to NT ($kg\,ha^{-1}\,y^{-1}$)	Eliminated Sf ($kg\,ha^{-1}\,y^{-1}$)	No fertilizer ($kg\,ha^{-1}\,y^{-1}$)	Permanent cover ($kg\,ha^{-1}\,y^{-1}$)
825	B–Sf–Ws	1.50	−0.51	2.36	−1.20	−1.50	0.31	−0.08	0.00	−0.17	−0.31
825	P–C–Sf	0.12	−0.03	0.28	−0.07	−0.12	0.30	−0.07	0.00	−0.16	−0.30
825	Ws–Sf–P	0.51	−0.23	0.38	−0.36	−0.51	0.27	−0.07	0.00	−0.14	−0.27
819	B–Sf–Ws	0.69	−0.24	0.83	−0.56	−0.67	0.17	−0.04	0.00	−0.11	−0.17
819	P–C–Sf	0.25	−0.08	−0.02	−0.19	−0.24	0.16	−0.04	0.00	−0.10	−0.16
819	Ws–Sf–P	0.34	−0.11	−0.03	−0.28	−0.34	0.15	−0.03	0.00	−0.09	−0.15
727	Ws–C–B–P–C	1.36	−0.75		−1.08	−1.35	0.90	−0.22		−0.67	−0.90
727	Ws–C–B–Sf–Fx	1.12	−0.60	−0.09	−0.64	−1.12	0.83	−0.21	0.00	−0.50	−0.83
727	Ws–P–B–Sf	0.77	−0.49	0.18	−0.31	−0.77	0.77	−0.22	0.00	−0.38	−0.77
760	Ws–P–Ws–C	1.33	−0.51		−1.29	−1.33	0.63	−0.15		−0.50	−0.63
760	Ws–P–Ws–Fx	1.31	−0.47		−1.28	−1.31	0.60	−0.14		−0.48	−0.60
760	Ws–Sf	0.19	−0.04	1.46	−0.16	−0.19	0.55	−0.16	0.00	−0.19	−0.55
760	Ws–Sf–C–Ws–Sf–P	0.84	−0.35	0.39	−0.81	−0.84	0.55	−0.14	0.00	−0.28	−0.55
760	Ws–Sf–C–Ww	1.17	−0.50	−0.08	−1.14	−1.17	0.70	−0.16	0.00	−0.44	−0.70
760	Ws–Sf–Fx	0.92	−0.34	0.74	−0.89	−0.91	0.55	−0.13	0.00	−0.30	−0.55
546	N	3.48	−0.27		−3.44	−3.47	3.27	0.33		−3.02	−3.27
546	Sb–A–A–A	2.04	0.02		−1.52	−2.02	0.96	0.38		−0.08	−0.96
546	B–B–A–A–A	3.17	−0.15		−2.08	−3.16	1.01	0.24		−0.40	−1.01
559	N–N–B–B	1.81	0.06		−1.78	−1.81	2.01	0.20		−1.80	−2.01
559	Sb	1.47	−0.05		−1.41	−1.47	1.15	0.12		−0.26	−1.15
559	B–B–B–A–A	1.73	−0.01		−1.52	−1.72	1.02	0.16		−0.54	−1.02
	Semi-arid	0.57	−0.20	0.63	−0.44	−0.56	0.23	−0.05	0.00	−0.13	−0.23
	Sub-humid	1.00	−0.45	0.43	−0.85	−1.00	0.67	−0.17	0.00	−0.42	−0.67
	Humid	2.28	−0.07		−1.96	−2.27	1.57	0.24		−1.02	−1.57

Negative values denote a reduction in GHG emissions.
Note: B, barley; Sf, summer-fallow; Ws, spring wheat; P, peas; Fx, flax; N, corn; Sb, soybean; Ww, winter wheat; C, canola.

Table 3
Estimated soil carbon change factors for changes in agricultural management calculated over 20 years. Emission factors for the management scenarios are relative to the base emission case.

Ecodistrict number	Rotation	DNDC estimated				Tier II/III estimated		
		No till (Mg C ha^{-1} y^{-1})	Eliminated Sf (Mg C ha^{-1} y^{-1})	No fertilizer (Mg C ha^{-1} y^{-1})	Permanent cover (Mg C ha^{-1} y^{-1})	No till (Mg C ha^{-1} y^{-1})	Eliminated Sf (Mg C ha^{-1} y^{-1})	Permanent cover (Mg C ha^{-1} y^{-1})
825	B–Sf–Ws	−0.09	−0.26	0.13	−0.71	−0.10	−0.30	−0.55
825	P–C–Sf	−0.10	−0.21	0.14	−0.71	−0.10	−0.30	−0.55
825	Ws–Sf–P	−0.10	−0.20	0.12	−0.72	−0.10	−0.30	−0.55
819	B–Sf–Ws	−0.03	−0.16	0.13	−0.36	−0.10	−0.30	−0.55
819	P–C–Sf	−0.02	−0.20	0.12	−0.38	−0.10	−0.30	−0.55
819	Ws–Sf–P	−0.03	−0.19	0.10	−0.39	−0.10	−0.30	−0.55
727	Ws–C–B–P–C	−0.13		0.17	−0.89	−0.15	−0.30	−0.54
727	Ws–C–B–Sf–Fx	−0.13	−0.34	0.15	−0.97	−0.15	−0.30	−0.54
727	Ws–P–B–Sf	−0.13	−0.26	0.12	−0.99	−0.15	−0.30	−0.54
760	Ws–P–Ws–C	−0.12		0.17	−0.72	−0.15	−0.30	−0.54
760	Ws–P–Ws–Fx	−0.12		0.16	−0.73	−0.15	−0.30	−0.54
760	Ws–Sf	−0.12	−0.35	0.13	−0.86	−0.15	−0.30	−0.54
760	Ws–Sf–C–Ws–Sf–P	−0.12	−0.31	0.15	−0.81	−0.15	−0.30	−0.54
760	Ws–Sf–C–Ww	−0.11	−0.43	0.16	−0.80	−0.15	−0.30	−0.54
760	Ws–Sf–Fx	−0.12	−0.30	0.16	−0.81	−0.15	−0.30	−0.54
546	N	−0.07		0.55	−0.52	−0.09		−0.71
546	Sb–A–A–A	−0.02		0.00	−0.49	−0.09		−0.71
546	B–B–A–A–A	−0.02		0.04	−0.48	−0.09		−0.71
559	N–N–B–B	−0.05		0.19	−0.63	−0.09		−0.71
559	Sb	−0.07		0.00	−0.54	−0.09		−0.71
559	B–B–B–A–A	−0.06		0.13	−0.60	−0.09		−0.71
	Semi-arid	−0.06	−0.21	0.12	−0.54	−0.10	−0.30	−0.55
	Sub-humid	−0.12	−0.33	0.15	−0.84	−0.15	−0.30	−0.54
	Humid	−0.05		0.15	−0.54	−0.09		−0.71

Negative values denote a carbon sink.
Note: B, barley; Sf, summer-fallow; Ws, spring wheat; P, peas; Fx, flax; N, corn; Sb, soybean; Ww, winter wheat; C, canola.

Table 4
Estimated combined GHG emission factors for changes in agricultural management calculated over 20 years. Emission factors for the management scenarios are relative to the base emission case.

Ecodistrict Number	Rotation	DNDC estimated				Tier II/III estimated		
		No till (Mg CO_2 eq. ha^{-1} y^{-1})	Eliminated Sf (Mg CO_2 eq. ha^{-1} y^{-1})	No fertilizer (Mg CO_2 eq. ha^{-1} y^{-1})	Permanent cover (Mg CO_2 eq. ha^{-1} y^{-1})	No till (Mg CO_2 eq. ha^{-1} y^{-1})	Eliminated Sf (Mg CO_2 eq. ha^{-1} y^{-1})	Permanent cover (Mg CO_2 eq. ha^{-1} y^{-1})
825	B–Sf–Ws	−0.58	0.19	−0.12	−3.34	−0.40	−1.10	−2.17
825	P–C–Sf	−0.39	−0.63	0.47	−2.66	−0.40	−1.10	−2.16
825	Ws–Sf–P	−0.49	−0.55	0.25	−2.88	−0.40	−1.10	−2.15
819	B–Sf–Ws	−0.21	−0.20	0.22	−1.66	−0.38	−1.10	−2.10
819	P–C–Sf	−0.13	−0.75	0.33	−1.50	−0.38	−1.10	−2.10
819	Ws–Sf–P	−0.15	−0.72	0.24	−1.59	−0.38	−1.10	−2.09
727	Ws–C–B–P–C	−0.84		0.10	−3.94	−0.66	−1.10	−2.42
727	Ws–C–B–Sf–Fx	−0.78	−1.31	0.25	−4.11	−0.65	−1.10	−2.38
727	Ws–P–B–Sf	−0.73	−0.86	0.31	−4.01	−0.66	−1.10	−2.35
760	Ws–P–Ws–C	−0.68		0.00	−3.28	−0.62	−1.10	−2.29
760	Ws–P–Ws–Fx	−0.66		−0.05	−3.32	−0.62	−1.10	−2.27
760	Ws–Sf	−0.45	−0.59	0.40	−3.25	−0.63	−1.10	−2.25
760	Ws–Sf–C–Ws–Sf–P	−0.61	−0.94	0.16	−3.36	−0.62	−1.10	−2.25
760	Ws–Sf–C–Ww	−0.64	−1.60	0.04	−3.50	−0.63	−1.10	−2.32
760	Ws–Sf–Fx	−0.60	−0.75	0.17	−3.40	−0.61	−1.10	−2.25
546	N	−0.40		0.34	−3.59	−0.17		−4.20
546	Sb–A–A–A	−0.07		−0.73	−2.78	−0.14		−3.07
546	B–B–A–A–A	−0.13		−0.87	−3.29	−0.21		−3.09
559	N–N–B–B	−0.15		−0.16	−3.20	−0.23		−3.58
559	Sb	−0.27		−0.69	−2.69	−0.27		−3.16
559	B–B–B–A–A	−0.22		−0.28	−3.05	−0.25		−3.10
	Semi-arid	−0.32	−0.44	0.23	−2.27	−0.39	−1.10	−2.13
	Sub-humid	−0.67	−1.01	0.15	−3.57	−0.63	−1.10	−2.31
	Humid	−0.21		−0.40	−3.10	−0.21		−3.37

Negative values denote a reduction in GHG emissions.
Note: B, barley; Sf, summer-fallow; Ws, spring wheat; P, peas; Fx, flax; N, corn; Sb, soybean; Ww, winter wheat; C, canola.

states in the US the soil C under NT did not differ from CT when the whole profile was taken into account. Angers et al. (1997) and Poirier et al. (2009) reported similar observations in cool humid soils. VandenBygaart et al. (2008) published a wide range of C storage rates (Table 2) across Canada, some indicating C loss after conversion from CT to NT. Most models include a tillage factor for conversion of CT to NT that increases with depth of tillage but this can result in considerable error for certain agroecosystems that

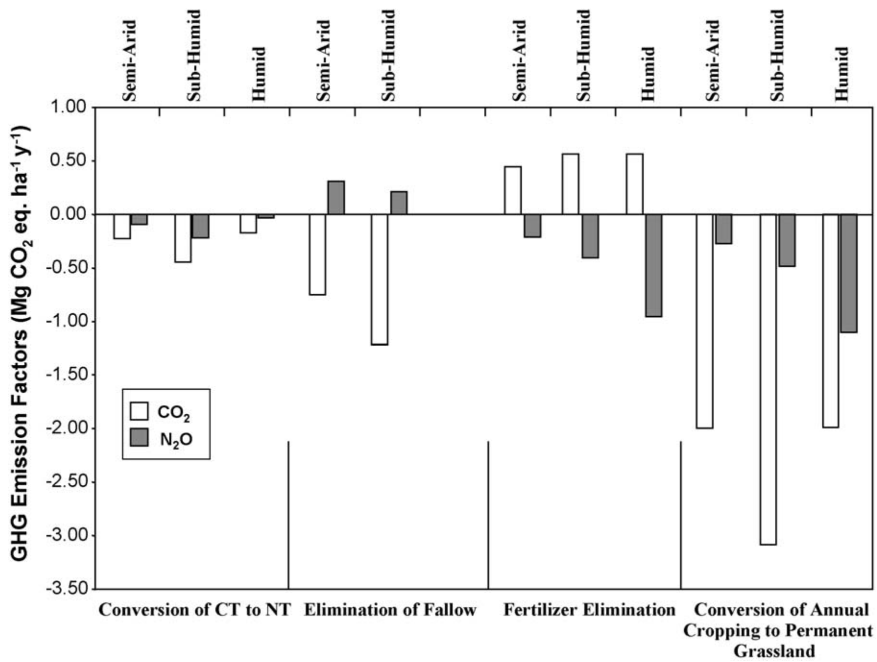

Fig. 2. GHG emissions factors estimated using the DNDC model for semi-arid, sub-humid, and humid climatic regions in Canada.

contain buried soil C. Where possible, multiple tillage factors should be developed for different tillage implements or by ploughing depth.

When removing fallow from rotation the DNDC model estimated average sequestration rates of $-0.21\ \mathrm{Mg\,C\,ha^{-1}\,y^{-1}}$ in semi-arid ecodistricts and $-0.33\ \mathrm{Mg\,C\,ha^{-1}\,y^{-1}}$ in sub-humid ecodistricts. This compares well with the value of $-0.3\ \mathrm{Mg\,C\,ha^{-1}\,y^{-1}}$ in VandenBygaart et al. (2008) which was derived from measured data. Keep in mind that these factors represent a complete change to fallow. Thus a 3-year wheat–wheat-fallow rotation in the sub-humid ecodistricts would have an overall factor of $-0.11\ \mathrm{Mg\,C\,ha^{-1}}$ if fallow was eliminated.

Not surprisingly, removal of fertilizer resulted in a loss of soil C except in the rotations with soybeans. About 20 kg $\mathrm{ha^{-1}}$ N was applied as starter to soybean during planting. Removal of this amount was not enough to cause a change in soil C, however it did cause a substantial reduction in N_2O emissions (Table 2). As determined by DNDC, the soybean crop was fixing enough N for production without the need of fertilizer and the excess N increased denitrification rates and production of N_2O.

The permanent cover soil C factors generated by the DNDC model was on average ($-0.64\ \mathrm{Mg\,C\,ha^{-1}\,y^{-1}}$) similar to estimates derived from our national inventory ($-0.60\ \mathrm{Mg\,C\,ha^{-1}\,y^{-1}}$), however, it is generally expected that higher factors occur in humid soils (VandenBygaart et al., 2008). The perennial grassland crop in the DNDC model may not be parameterized optimally (water requirement, perhaps N-fixation) for cool climate conditions.

3.4. GHG emission factors

GHG emissions from combined CO_2 and N_2O emission factors indicate that all management practices except for fertilizer elimination in western Canada will lower GHG emissions (Table 4). In western ecodistricts, reduced N_2O emissions when fertilizer was removed could not compensate for high rates of soil C loss. The combined factors for conversion of CT to NT as determined by DNDC were found to be significant at the 0.1 level to those used to generate Canada's national inventory (Tier II/III methodology). The DNDC model estimated higher N_2O factors whereas estimates from Tier II/III methodology showed greater rates of soil C sequestration. The combined permanent cover factors for semi-arid and sub-humid soils were similar between DNDC and Tier II/III. The combined factor determined by DNDC for permanent cover in sub-humid soil was high due to the high predicted rate C sequestration by the model in this climatic region (Table 3).

The overall magnitude of the soil C factors, as estimated by the DNDC model, was greater than the N_2O emission factors (Fig. 2). This is particularly true in western Canada where 80% of the agricultural land in the country is situated. These observations are consistent with those made by Smith and Bertaglia (2007) who estimated that 90% of the total mitigation potential comes from sink enhancement. Note that promising technologies such as precision fertilizer management and nitrification inhibitors which can substantially decrease N_2O emissions were not included in our assessment. Also, it should be noted that changes in future management can quickly undo years of carbon sequestration.

Table 5
Comparison of linearly additive factors for conversion of CT to NT and removal of fallow versus factors for the combined management change.

Ecodistrict number	Rotation	N_2O-N factors (20 years)			Carbon factors (20 years)		
		Combined ($\mathrm{kg\,ha^{-1}\,y^{-1}}$)	Additive ($\mathrm{kg\,ha^{-1}\,y^{-1}}$)	Change (%)	Combined ($\mathrm{Mg\,C\,ha^{-1}\,y^{-1}}$)	Additive ($\mathrm{Mg\,C\,ha^{-1}\,y^{-1}}$)	Change (%)
819	A–A–A–A–Sf–Ws–C	−0.14	−0.19	29.5	0.122	0.129	5.4
819	B–Sf–Ws	0.47	0.60	26.1	0.085	0.080	−5.2
819	P–C–Sf	−0.06	−0.10	53.7	0.091	0.092	0.4
819	Ws–Sf–P	−0.11	−0.14	22.2	0.091	0.091	0.3

3.5. Linearly additive factors versus factors for combined management

The DNDC-MFT offers the advantage of simulating more than one management practice at a time and to determine a combined factor for different permutations of agricultural management. Only one simple example was modeled instead of a more robust set of permutations of management as there is very little data available for comparison (Table 5). In this example linearly additive factors generated by DNDC were compared with a factor for the combination of management change of CT to NT and reduction in fallow. The N_2O factors differed between the linearly additive and combined methodologies indicating that the two management practices interacted dynamically with each, however, it is interesting to note that C factors were similar.

4. Conclusions

The DNDC-Management Factor Tool was developed in order to generate soil C and direct N_2O emission factors for changes in agricultural management for any of 462 ecodistricts across Canada. The structure of DNDC-MFT was developed to allow easy incorporation of improved versions of the DNDC model and the possibility to be adapted for other process-based models. Estimating rates of C change and N_2O emissions across the range of soils, climates, and agricultural managements that occurs within a country the size of Canada can be challenging, not only from the perspective of the processes considered in the model but also due to inconsistencies in input data gathered over vast areas and long time periods. Even though considerable progress has been made in developing models that can predict the relative magnitude of GHG emissions, it is still quite a challenge to predict accurately change in emissions based on changes in management. In this study, it was shown that the DNDC model was able to provide reasonable emission factors for most changes in agricultural management. Estimated soil C change factors for conversion of CT to NT were likely too high for eastern Canada but were within the variability of mean measured values. The model had difficulty in predicting accurately the differences in soil–water regime between CT and NT systems and as a result N_2O emissions may have been under estimated under NT management. As our understanding of C and N cycles keeps improving, DNDC-MFT will be very useful for assessing the performance of improved versions of the DNDC model and will serve as an excellent tool for estimating emission factors for individual change in management or combinations of management changes.

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