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DNDC: A process-based model of greenhouse gas fluxes from agricultural soils

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ABSTRACT

The high temporal and spatial variability of agricultural nitrous oxide (N_2O) emissions from soil makes their measurement at regional or national scales impractical. Accordingly, robust process-based models are needed. Several detailed biochemical process-based models of N-gas emissions have been developed in recent years to provide site-specific and regional scale estimates of N_2O emissions. Among these DNDC (Denitrification–Decomposition) simulates carbon and nitrogen biogeochemical cycles occurring in agricultural systems. Originally developed as a tool to predict nitrous oxide (N_2O) emissions from cropping systems, DNDC has since been expanded to include other ecosystems such as rice paddies, grazed pastures, forests, and wetlands, and the model accounts for land-use and land-management effects on N_2O emissions.

As a process-based model, DNDC is capable of predicting the soil fluxes of all three terrestrial greenhouse gases: N_2O, carbon dioxide (CO_2), and methane (CH_4), as well as other important environmental and economic indicators such as crop production, ammonia (NH_3) volatilisation and nitrate (NO_3^-) leaching. The DNDC model has been widely used internationally, including in the EU nitrogen biogeochemistry projects NOFRETETE and NitroEurope.

This paper brings together the research undertaken on a wide range of land-use and land-management systems to improve and modify, test and verify, and apply the DNDC model to estimate soil–atmosphere exchange of N_2O, CH_4 and CO_2 from these systems.

1. Introduction

Agricultural soils can act as a source or a sink for the three greenhouse gases, nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4). The fluxes of these gases derive from biological processes and depend on many factors that sometimes have complex feedbacks and interactions. Understanding the impacts of human activities on greenhouse gas emissions from productive soils is vital for mitigating negative effects on climate change while continuing to feed the Earth's increasing population.

As greenhouse gas emissions from soils are the result of microbial processes, the emissions exhibit a high degree of temporal and spatial variability. Direct measurement of greenhouse gas emissions for inventory purposes is impractical as it would require many measurements to be made over large areas and for long periods of time. Many countries use the IPCC default methodology for calculating N_2O emissions from agricultural soils for their national inventories. This method simply assumes a fixed proportion (the "emission factor") of the applied N is emitted as N_2O. The emission factor was deduced from a limited number of observations but represents an average value over all soil types, climate conditions and management practices. As N_2O emissions are highly sensitive to all these factors there is a high degree of uncertainty associated with the emission factor. In addition, the emission factor method does not account for many of the management practices that could potentially reduce N_2O emissions (e.g., fertiliser timing, splitting fertiliser applications, use of nitrification inhibitors, depth of application). For these reasons the development of a more process-based approach is desirable.

The development of a process-based model not only allows the simulation of agricultural greenhouse gas emissions at a range of scales up to national or global level, but also the exploration of potential mitigation strategies. In addition, because the DNDC model simulates the interactions between the different soil processes, it is possible to determine how strategies that reduce the emission of one gas will affect emissions of the other gases, and whether there may be other adverse consequences (e.g., reduced production or increased nitrate leaching).

The DNDC model was originally developed to simulate N_2O emissions from cropped soils in the US (Li et al., 1992a; US EPA, 1995). It has since been used and expanded by many research groups covering a range of countries and production systems. In

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this paper we describe the DNDC model and how it has been developed, validated and used, including regional and national scale simulations, sensitivity analysis and scenario assessment.

2. Model description

As discussed in the introduction DNDC was first used to model N_2O emissions from agricultural soils in the US (US EPA, 1995). Since its initial development (Li et al., 1992a), other researchers have modified the model to adapt it to other production systems and many of these modifications have been incorporated into later versions of the DNDC model. DNDC consists of five interacting sub-models: thermal–hydraulic, aerobic decomposition, denitrification, fermentation, and plant growth (which contains sub-routines for handling management practices such as crop rotation, tilling, irrigation, and fertiliser and manure addition). The first three sub-models are described in Li et al. (1992a), while Li et al. (1994a) describes the plant growth and land-management sub-models. A dynamic scheme describing soil redox potential evolution was added in DNDC for simulating fermentation processes (Li, 2000, 2007). Simulations of N_2O, CH_4 and NH_3 are described in Li (2000, 2007). Fig. 1 shows how the different components of the model interact.

DNDC treats the soil as a series of discrete horizontal layers (down to a depth of 50 cm). Within each layer all the soil properties are assumed to be uniform. Some of the soil physical properties such as bulk density, porosity and hydraulic parameters are assumed to be constant across all layers; however, most of the soil properties (e.g., soil moisture, temperature, pH, carbon and nitrogen pools) can vary between layers. Calculations are then performed on each soil layer for each time step.

The default soil parameters in DNDC were based on average values for US soils. Researchers in other countries frequently need to re-parameterise the soil properties for local conditions and sometimes choose to modify the model equations to better match these local conditions. Many researchers have created variants of DNDC for specific systems (e.g., Wetland-DNDC, Forest-DNDC, NZ-DNDC, UK-DNDC).

2.1. Plant growth

Plant growth is modelled in the “standard” DNDC using a daily crop growth curve (specific to the plant type) to calculate the daily N-uptake required. This N is extracted from the available soil NO_3^- and NH_4^+ pools (in proportion to the relative size of each pool) down to the plant root depth. The daily growth rate is subject to the modelled availability of water and N in the soil profile. A more detailed physiological/phenological model of plant growth (Crop-DNDC) was developed by Zhang et al. (2002a) and can be used as an alternative to the standard plant growth model when more detailed plant growth data are available.

2.2. Soil moisture

The original DNDC did not simulate soil freezing and thawing effects on N_2O estimates in systems where soil froze. During the development of PnET-N-DNDC, a routine algorithm was developed to track the impacts of soil freezing and thawing processes on N_2O production based on the detailed field data observed from a forest stand in Germany (Li et al., 2000). This algorithm was modified by Xu-Ri et al. (2003a) to better simulate emissions from semi-arid grasslands in Inner Mongolia. These included changing the nitrification sub-model to include soil NH_4^+ levels (rather than just the decomposition rate) to calculate substrate available for nitrification, stopping N_2O production when a soil layer is <-1 °C, limiting heat transfer from air to soil through snow insulation and

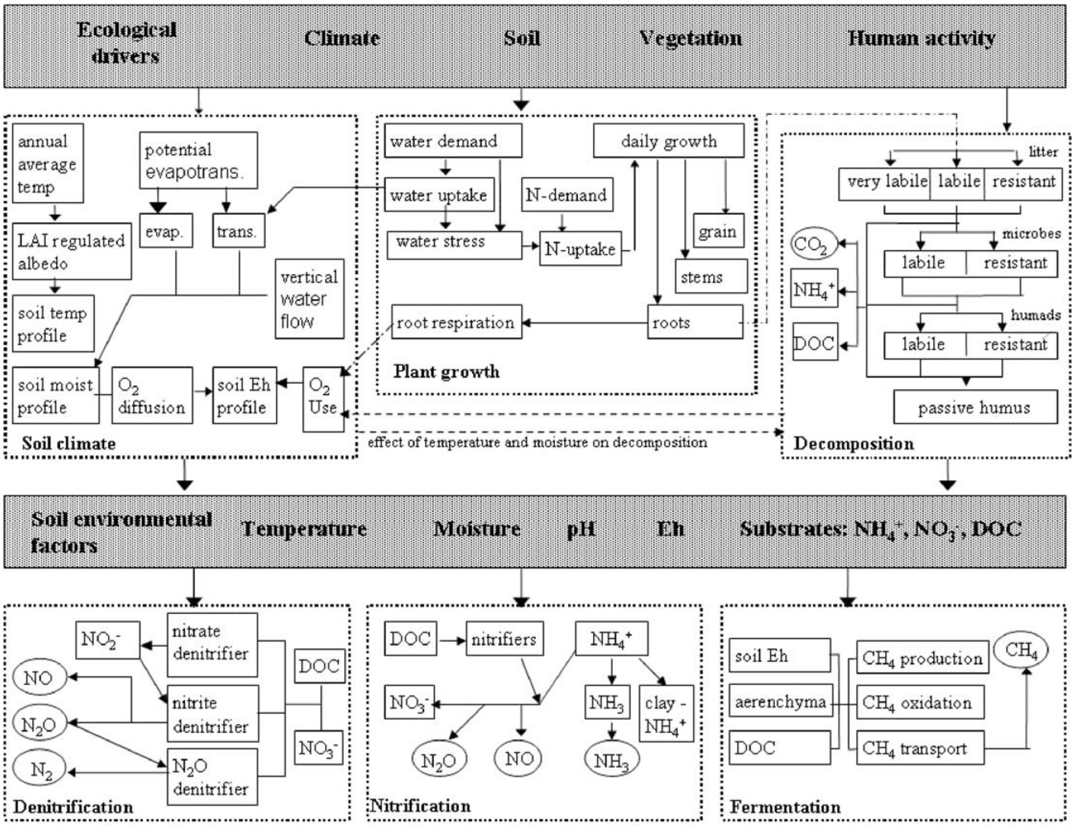

Fig. 1. Schematic diagram of DNDC model structure (adapted from Li, 2000).

assuming that if the soil is snow covered or soil layers are frozen, 3% of produced N_2O will escape to the air.

Additional changes to the water drainage and N adsorption to better simulate measured NO_3^- leaching were recently incorporated (Li et al., 2006).

2.3. Anaerobic balloon

The nitrification/denitrification scheme was improved using the concept of an "anaerobic balloon" which swells or shrinks according to redox potential of the soil (Li et al., 2004a). For each layer substrates (such as DOC, NH_4^+ and NO_3^-) were allocated to the anaerobic or aerobic compartments based on oxygen availability. This enabled the nitrification and denitrification to occur simultaneously.

2.4. Forest and wetland systems

The PnET-N-DNDC model was created to model greenhouse gas emissions from forest systems by combining the PnET model (Aber and Federer, 1992) with DNDC (Li et al., 2000).

Kiese et al. (2005) applied the PnET-N-DNDC model to a tropical rainforest. This required some modifications as the original model had been developed for temperate systems. The changes included adjusting the forest physiology and soil parameters for tropical conditions, allowing forest growth throughout the year, modifying the daily leaf litterfall equations, incorporating biological N-fixation, and incorporating an activity index for denitrifier populations that decreases with time if the soil is dry and increases when the soil is wet.

Wetland-DNDC (Zhang et al., 2002b; Li et al., 2004a) is a modified version of PnET-N-DNDC designed to simulate wetland systems (on both mineral and organic soils) where water table dynamics, as well as soil properties and climate, affect C-cycling and greenhouse gas emissions. The Wetland-DNDC model was further modified to account for managed forest systems by parameterizing management practices and refining the anaerobic biogeochemical processes (Li et al., 2004a; Cui et al., 2005). An integrated version of the Wetland-DNDC and PnET-N-DNDC models is called Forest-DNDC.

2.5. Grazed pastures

For New Zealand, Saggar et al. (2004, 2007a) modified the DNDC model to better simulate the year-round grazed pasture systems. The changes made included: (i) creating a perennial pasture growth module, as the original model only had seasonal crop growth module; (ii) reversing the order in which soil infiltration and drainage processes were calculated to enable the soils to become fully saturated; (iii) using a New Zealand specific relationship between air temperature and soil surface temperature; (iv) changing the soil moisture threshold to above field capacity rather than the fixed 35% WFPS for denitrification process based on recent experimental observations from laboratory and field studies of pastoral soils; (v) quantifying the N inputs from grazing animals; and (vi) modifying the potential evapotranspiration to use the Priestley and Taylor equation that better predicted measured soil moisture rather than the Thornthwaite formula. Cattle treading causes compaction, so reduced water flow was simulated using the "water retention layer" function that had been developed to simulate reduced water flow due to ice layers in Canadian soils.

While there is good agreement between the NZ-DNDC predictions and measured N_2O emissions for dairy-grazed, sheep-grazed and farm dairy effluent irrigated systems (Fig. 2) these campaigns were conducted in the same region and included only two different soil types. However, these are the only New Zealand studies where field scale measurements of emissions have been made under grazing conditions across all the seasons of the year.

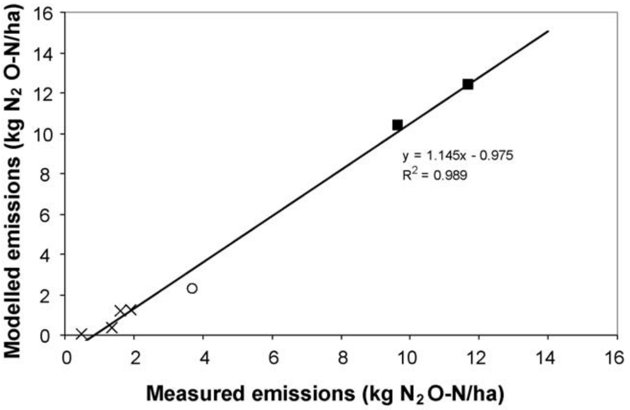

Fig. 2. Comparison of measured N_2O emissions in New Zealand with the emissions predicted using NZ-DNDC. The black squares (■) represent dairy-grazed pastures (data from Saggar et al., 2004), the white circle (○) sheep-grazed pasture (data from Saggar et al., 2007b) and the crosses (×) a dairy farm effluent irrigated system (data from Bhandral, 2005).

2.6. Manure-DNDC

To respond to the increasing demand for tools to quantify greenhouse gas and ammonia emissions from livestock operation systems, Li and his colleagues recently developed a new version of DNDC, the Manure-DNDC model. In Manure-DNDC, the biogeochemical reactions (e.g., decomposition, hydrolysis, ammonium–ammonia equilibrium, ammonia volatilisation, nitrification, denitrification and fermentation) parameterised in DNDC have been linked to dynamics of the environmental factors (e.g., temperature, moisture, pH, Eh and substrate concentration gradients) for each of the farm management facilities (e.g., feeding lot, compost, lagoon, anaerobic digester, manure land application). The model is capable of estimating the greenhouse gas inventory, and predicting impacts of alternative management practices (e.g., feed types, housing, manure storage/treatment) on greenhouse gas mitigation for a wide range of farm types (Li et al., manuscript ready for submission to Global Biogeochemical Cycles).

3. Model validation

Validation against experimental data is an essential part of model development. If experimental measurements agree well with model predictions, there is increased confidence that the model is correctly simulating the underlying processes. On the other hand, in cases where the model fails to predict the measurements this can help identify processes that the model simulates poorly.

DNDC has now been used to simulate various cropping, grazing and forest systems in many countries. Table 1 lists some published validation studies of DNDC. The agreement between the model simulations and measured values vary, with some studies reporting poor agreement. The DNDC model is very sensitive to climate, soil, and crop inputs, so in some cases errors may be introduced when auxiliary inputs are not measured on-site. It is also important to note that the DNDC model continues to be improved as more experimental data become available, so later versions of DNDC will have corrected some of the problems found in earlier versions.

Table 1
Validation studies comparing DNDC predictions against experimental measurement. Note that not all the listed properties were tested at each site.

Reference	Systems modelled	Predicted properties	Countries	Version (if stated)
Babu et al. (2005)	Rice	Grain yield; CH_4 emission	India	
Babu et al. (2006)	Rice, Rice-Wheat	N_2O, CH_4	India	
Beheydt et al. (2007)	Grassland; Crops	Soil NH_4^+, NO_3^-, WFPS, N_2O	Belgium	DNDC 8.3P
Beheydt et al. (2008)	Crops	Soil NH_4^+, NO_3^-, WFPS, N_2O	Belgium	DNDC 8.3 P
Brown et al. (2002)	Grassland; Winter wheat	N_2O	UK	UK-DNDC
Cui et al. (2005a)	Forested wetland	CH_4; N_2O; Net ecosystem carbon exchange	USA	Wetland-DNDC
Cui et al. (2005b)	Forested wetland	CH_4, CO_2, SOC, gross photosynthesis	USA	Wetland-DNDC
Cui et al. (2005)	Forested wetland	CH_4, net ecosystem carbon exchange	USA	Wetland-DNDC + MIKE SHE
Frolking et al. (1998)	Grazed rangeland; Grass ley; Crop rotations	N_2O, soil WFPS; soil NO_3^-, soil NH_4^+	USA; Scotland; Germany	
Grant et al. (2004)				
Hsieh et al. (2005)	Grazed grassland	N_2O	Ireland	
Kesik et al. (2005)	Forest	N_2O, NO	Multiple sites across Europe	PnET-N-DNDC
Kiese et al. (2005)	Tropical rainforest	N_2O	Australia; Costa Rica	PnET-N-DNDC
Lamers et al. (2007a)	Forest	N_2O	Germany	Forest-DNDC 3.7W
Lamers et al. (2007b)	Forest	N_2O	Germany	Wetland-DNDC
Li et al. (1992b)	Native shortgrass prairie; Fallow (organic soil); Cut ryegrass; Grassland; Winter wheat	N_2O; $(N_2 + N_2O)$; CO_2	USA; England; Germany	
Li et al. (1994a)	Wheat straw on bare soil; Grassland; Winter wheat; Crop rotations	% Undecomposed residue; CO_2 emission; long-term SOC	Costa Rica; Germany; USA; England	
Li et al. (1994b)	Bare soil; St Augustine grass; Sugarcane	N_2O; soil NO_3^-	USA	
Li et al. (1997)	Grass; Crop rotations	SOC	England; Australia; Germany; Czech Republic	
Li (2000)	Winter wheat; Maize; Rice	NO; N_2O; CH_4; NH_3	China; Costa Rica; USA	
Lu et al. (2008)	Forest (*Abies fabric*)	Soil CO_2	China	Forest-DNDC
Miehle et al. (2006a)	Eucalyptus	Above ground C	Australia	Forest-DNDC
Pathak et al. (2005)	Rice	Grain yield, total biomass, crop N uptake, CH_4, N_2O	India	
Saggar et al. (2004)	Dairy-grazed pasture	N_2O, soil WFPS	New Zealand	NZ-DNDC
Saggar et al. (2007b)	Sheep-grazed pasture	N_2O, CH_4	New Zealand	NZ-DNDC
Smith et al. (2002)	Crops	N_2O	Canada	DNDC 7.1
Smith et al. (2008)	Crops	Soil temperature, NO_3^-, NH_4^+, moisture content, N_2O	Canada	
Stange et al. (2000)	Temperate forest	N_2O, NO, soil WFPS	USA, Austria, Denmark, Germany	PnET-N-DNDC
Wang et al. (1997)	Pasture	N_2O, CO_2	Australia	Modified DNDC
Xu-Ri et al. (2003a)	Semi-arid grassland	N_2O; soil T; WFPS	China (Inner Mongolia)	
Zhang et al. (2002a)	Winter wheat; Rice; Corn	Soil water, LAI, above ground biomass, biomass of each organ; plant N	China; USA	Crop-DNDC

DNDC predictions of soil emissions of N_2O, NO, CH_4 and CO_2, plant growth, soil organic carbon (SOC), soil NO_3^- and NH_4^+ have been published (see Table 1). However, no study has yet examined all of these factors simultaneously. Soil water-filled pore space (WFPS) is an important driver for many of the soil processes producing these emissions, and for this reason many studies also examine the model predictions of WFPS.

The DNDC model has been compared with other similar models. Frolking et al. (1998) compared N_2O flux simulations from DNDC and three other process-based models with field measurements from five temperate agricultural sites in three countries. The models produced similar results for the general patterns of soil nitrogen dynamics through the agro-ecosystems, but simulated trace gas fluxes were quite different due to different processes embedded in the models.

Beheydt et al. (2007) compared DNDC predictions with 22 long-term N_2O field measurements in Belgium. The model simulated N_2O emissions from croplands well ($P = 1.08 \times O + 7.4$, $R^2 = 0.85$) but performed poorly on grassland systems ($P = 0.42 \times O + 7.2$, $R^2 = 0.16$).

4. Sensitivity analyses

Sensitivity analysis involves testing the model performance as various inputs are changed. This helps determine which inputs are having the greatest effect on the predicted emissions and whether the model has captured observed differences in emissions under different management strategies. Identifying input parameters that have a large effect on predicted emissions can be used to quantify and/or reduce the uncertainty in the model predictions arising from uncertainty in the input parameters. Sensitivity analysis differs from validation as it does not compare the model output with field data.

4.1. Soil and climate effects

N_2O emissions can occur via nitrification or denitrification; with nitrification occurring under aerobic conditions and denitrification occurring under anaerobic conditions. Both processes can also occur simultaneously due to anaerobic microsites within the soil. Accordingly, soil moisture status strongly influences N_2O

emissions and higher precipitation tends to increase periods of anaerobic soil conditions. Li et al. (1992a) found for total denitrification ($N_2O + N_2$) annual precipitation had the greatest effect of the properties examined followed by soil pH. However, increasing the annual precipitation slightly decreased N_2O due to a greater proportion of the denitrification reactions continuing to N_2. Saggar et al. (2007a) also found a decrease in net N_2O emissions (i.e. the total emissions minus the emissions in the absence of applied fertiliser or excretal N) with increasing rainfall due to increased NO_3^- leaching. In contrast, Stange et al. (2000) found for a forest system that N_2O emissions increased with precipitation using the PnET-N-DNDC model. Brown et al. (2002) found N_2O emissions increased with both increases and decreases in precipitation from the baseline of ~600 mm per annum. The complexity of relations between N_2O emissions and environmental factors demonstrated from the sensitivity tests could be explained with the N_2O-controlling mechanisms embedded in DNDC. In DNDC, N_2O production/consumption is directly regulated by three factors namely soil redox potential (Eh), DOC concentration and available N (i.e. ammonium or nitrate) concentration. When natural processes or management changes, they simultaneously alter these three driving factors, and N_2O production will decrease if any of the factors becomes limiting.

Clay content and soil bulk density both influence N_2O emissions. For example, Li et al. (1992a) found increased clay content decreased N_2O emissions while bulk density increased them. The effect of clay content is due to its effect on the soil hydrological conditions, while the effect of bulk density is due to the implicit increase in SOC (defined as kg C/kg soil) from increasing the mass of soil. Similarly, increasing the SOC directly resulted in increased N_2O emissions. Increasing temperature generally resulted in increased N_2O emissions due to increased microbial activity. N_2O emissions were also slightly increased by increased N in rainfall.

The effect of clay content on N_2O emissions is due to the effect of clay on soil hydraulic properties. Some studies (e.g., Rochette et al., 2008) have found high N_2O emissions in soils with high clay content due to increased moisture content. Early versions of DNDC were not able to accurately simulate saturated soil conditions due to low hydraulic conductivity, as the model automatically drained the soil to field capacity. However, more recent studies have improved the modelling of soil moisture. In the NZ-DNDC model (Saggar et al., 2004), the order of the soil drainage and water infiltration procedures were reversed so that water contents greater than field capacity were possible. Li et al. (2006) implemented a recession curve to describe water discharge during and after a rainfall event.

4.2. Management practices

The effects of management practices on soil greenhouse gas emissions can be simulated using DNDC. Many management practices have a significant impact on greenhouse gas emissions, although the degree of impact can often depend on the soil and climate properties. Increased levels of fertiliser application generally result in increased N_2O emissions while increasing the depth of application reduces emissions (Brown et al., 2002; Li et al., 1994b, 1996). Emissions are also sensitive to the timing of fertiliser (or grazing) applications (Brown et al., 2002; Saggar et al., 2002). Manure additions led to a high rate of N_2O emissions in simulated corn cropping in Iowa (Li et al., 1996) while no-till practices reduced emissions.

Brown et al. (2002) also found that the effect of fertiliser type was very significant but depended on the baseline soil conditions.

Greenhouse gas emissions from rice paddies have been simulated using DNDC (Li et al., 2001, 2004b; Babu et al., 2005, 2006; Pathak et al., 2005). Application of mid-season drainage was found to reduce CH_4 emissions. However, some of the benefit of this practice was offset by increased N_2O emissions. Emissions of N_2O were unaffected by fertiliser applications up to 180 kg N ha^{-1} as the continuously flooded fields inhibited the process of nitrification transforming NH_4^+ into NO_3^-. Substituting 60 kg ha^{-1} urea N with farmyard manure N increased greenhouse gas emissions due to the increased organic C content (Pathak et al., 2005).

A wide range of alternative management practices are available to mitigate greenhouse gas emissions across climatic zones, soil types and management regimes for terrestrial ecosystems, based on the sensitivity testing of DNDC (e.g., Beheydt et al., 2008; Cui et al., 2005a; Grant et al., 2004; Qiu et al., 2009).

5. Model uncertainty

Sensitivity analyses can be used to estimate the degree of uncertainty in the model predictions resulting from imperfect knowledge of the input parameters. This is particularly relevant for regional scale simulations where inputs are derived from GIS databases. These uncertainties can be estimated using Monte Carlo simulations, in which a large number of possible scenarios are generated using random values (within a specified range) for each input parameter. The set of predicted values can then be analysed statistically to see the likely range and distribution of the model predictions as the input parameters are varied.

However, as Monte Carlo simulations are computationally expensive, the simplified Most Significant Factor (MSF) method is used in most regional simulations. The MSF method involves taking the extreme values of the factor(s) producing most of the variation in the model predictions. Li et al. (1996) examined the range of soil parameters in seven States in the US and ran DNDC simulations using the extreme values of each parameter with the median values of the other parameters to find MSFs with respect to each model output. Using the extreme SOC values produced a range of N_2O flux predictions that covered the range produced by varying any other single parameter. This range also covered 34–80% of the range of fluxes predicted using the extreme values of all the soil parameters. Clay content, bulk density and initial SOC were the key driving variables (of the 11 examined) for predicting N_2O emissions in forest and pasture systems in Costa Rica (Plant, 1998). Butterbach-Bahl et al. (2004) found SOC to be the most sensitive parameter for N_2O from agricultural soils, while NO emissions were also sensitive to soil texture.

Kesik et al. (2005) compared the range of N trace gas fluxes in forest systems predicted by PnET-N-DNDC using the MSF and

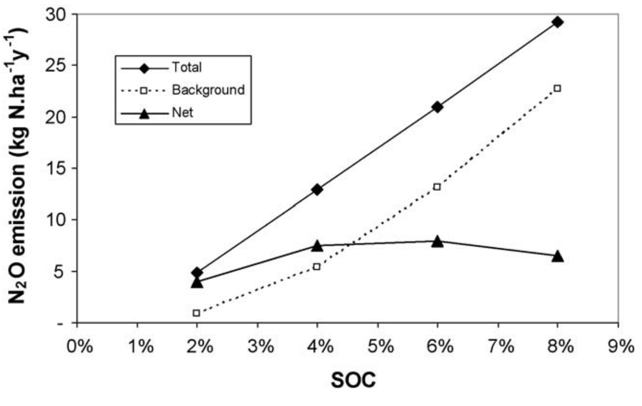

Fig. 3. N_2O emissions simulated by NZ-DNDC for a typical well-drained dairy system with SOC varied from 2 to 8%. The "background" represents the simulated emissions with no applied fertiliser or excretal N (Giltrap et al., 2008).

Monte Carlo methods. For the MSF method, the maximum scenario used a combination of maximum organic matter mass, minimum pH, minimum stone content, and maximum clay. The NO emissions predicted using the MSF method covered on average over 79% of the variability of the Monte Carlo method. However, for N_2O emissions the MSF method predicted maximum values that were on average only 50% of the Monte Carlo values.

There is a potential pitfall when applying the MSF identified for total N_2O emissions to net N_2O emissions (i.e. the emissions remaining after the "background" N_2O emissions in the absence of applied N have been subtracted). While SOC has been identified as the MSF for total N_2O emissions, background N_2O emissions are also affected by SOC, and taking the two extreme values of SOC does not necessarily produce the extreme values for net N_2O emissions. This is illustrated in Fig. 3 (from Giltrap et al., 2008).

6. Regional inventories

DNDC can be used to estimate greenhouse gas emissions at regional or national scales. At the regional scale, the region is first divided into smaller units ("cells") that can be considered to have uniform soil and climate properties. Second, climate and the range of each soil property within the unit are determined, usually from GIS databases. Typical farm management practices for the major farm types within the region are then defined, and the area under each farming system within each cell is specified. The DNDC model is then run for each farm type in each cell, usually twice, using the extreme values of the MSFs to estimate the uncertainty in the model predictions.

Table 2 lists several published studies that have used DNDC to estimate emissions at regional scale.

Regional analysis can be useful for identifying areas or farm systems with particularly high emissions. For example, Li et al. (1994b) found that six counties in Florida accounted for approximately 50% of the states N_2O emissions. These areas with high emissions can then be targeted for mitigation projects where they could have the greatest impact.

Weather variations between years can also cause variation in model predictions. Smith et al. (2004) found N_2O emissions for Canada over the period 1990–1999 averaged 46.7 Gg N_2O-N but varied from 29.6 to 77.0 Gg N_2O-N due to variation in climate data. Other researchers have found variations in N-trace gas emissions of up to 36% resulting from interannual changes in climate data (Butterbach-Bahl et al., 2004; Giltrap et al., 2008).

7. Scenario analyses

Scenario analysis involves using the model to explore the potential impacts of changes to production systems. In some ways this is similar to sensitivity analysis, except that usually combinations of changes are compared rather than just the effects of individual parameters. There are two major areas of interest for scenario analysis using DNDC. One is the effects of climate variability and potential climate change on greenhouse gas emissions, while the other is the potential for different mitigation strategies to reduce these emissions. One advantage of using DNDC is that it allows for simulations of soil emissions of the three major agricultural greenhouse gas emissions. This allows emission strategies to take into account their net impact on greenhouse gas emissions (as well as other environmental or economic impacts).

Different mitigation strategies can then be compared to assess which could potentially produce the greatest benefit. Scenario analyses can also be used to explore the impacts of climate change on agricultural production and emissions.

The potential impacts of climate change (using the Hadley centre model output for the IS92a scenario for 2070–2100) on N_2O emissions in Ireland from an intensively grazed and fertilised pasture were studied by Hsieh et al. (2005). The increased year round temperatures (+2.0–2.5 °C) and winter precipitation (+0.55 mm d^{-1}) were predicted to increase the annual N_2O emissions by 45%, assuming the same rate of N application, with the bulk of the extra emissions occurring in spring and autumn. This increase was greater than the predicted 6% reduction in N_2O emissions resulting from environmental legislation currently being implemented across Europe that will restrict fertiliser N application to 170 kg ha^{-1}.

The average impacts of changes in agricultural management practices on N_2O and CO_2 emissions from Canada were examined by running multi-year scenarios for Canada's major soil and crop types (Grant et al., 2004). Considering the effects of both N_2O and CO_2, three of the six management practices examined were found to have a net greenhouse gas benefit. These were conversion of cropland to grassland, conversion of conventional tillage to no-

Table 2
Regional studies using the DNDC model.

Reference	Region	Production systems	Predicted property	Model version (if stated)
Brown et al. (2002)	UK	Agriculture	Net N_2O, leached NO_3^-, NH_3 volatilised (used to calculate indirect N_2O)	UK-DNDC
Butterbach-Bahl et al. (2004)	Saxony, Germany	Agriculture and forest	N_2O and NO	DNDC and PnET-N-DNDC
Giltrap et al. (2008)	Manawatu-Wanganui, New Zealand	Agriculture	Net N_2O	NZ-DNDC
Kesik et al. (2005)	Europe	Forest	N_2O and NO	PnET-N-DNDC
Kiese et al. (2005)	'Wet tropics' region in Australia	Forest	N_2O, soil CO_2	PnET-N-DNDC
Levy et al. (2007)	Europe	Grasslands	CO_2, CH_4, N_2O	DNDC 8.3P
Li et al. (1994b)	Florida, USA	Agriculture	N_2O	
Li et al. (1996)	47 contiguous states, USA	Agriculture	N_2O	
Li et al. (2001)	China	Arable	N_2O	
Li et al. (2004b)	China	Rice	N_2O, CH_4, CO_2	
Neufeldt et al. (2006)	Baden-Württemberg	Agriculture	N_2O and CH_4	DNDC coupled with EFEM
Pathak et al. (2005)	India	Rice	CH_4, N_2O and CO_2	
Pathak et al. (2006)	Indo-Gangetic Plain, India	Rice-Wheat	NH_3 volatilisation, NO_3^- leaching, denitrification, N uptake by plants	
Plant (1998)	Northern Limón Province, Costa Rica	Forests, plantations forests and pasture	N_2O	
Werner et al. (2007)	Global	Tropical rainforests	N_2O	ForestDNDC-tropica

tillage, and reduction of summer fallow from the crop rotation. The magnitude of these benefits varied with soil type.

Li et al. (2004b) found that applying mid-season drainage to a rice paddy substantially decreased CH_4 emissions based on sensitivity tests. The benefit of this was partially offset by increased N_2O emissions, but there was still a net reduction in the global warming potential of the emissions. Regional simulations were then run across the rice growing regions of China and it was found that a change from continuous flooding to midseason drainage reduced CH_4 emissions by 1.7–7.9 Tg C/yr but increased N_2O emissions by 0.13–0.20 Tg N/yr (offsetting 65% of the reduction in global warming potential from CH_4).

Chinese farmers have started gaining C credits by incorporating more crop residue in their soils or resuming traditional manure fertiliser. However, when DNDC was used to simulate the effects of these practices soil N_2O and CH_4 emissions increased across the major agricultural regions in China. The greatest benefit for mitigation could be gained from combining the SOC-sequestration strategies with reduction of synthetic fertiliser use (Qiu et al., 2009).

8. Discussion

The biogeochemical processes that produce greenhouse gas emissions from soil are complex and involve many feedback mechanisms. It is therefore difficult to develop simple empirical models that can reliably predict greenhouse gas emissions over a range of different soil conditions and management practices. By seeking to simulate the underlying processes, models such as DNDC are better able to predict emissions from a wide range of systems. Already DNDC has been adapted to simulate cropping, pastoral and forest systems in a number of countries.

Assessing the "goodness of fit" of the model predictions is not always straight-forward. There are a number of metrics that have been developed to assess the "goodness of fit". Two commonly used measures are the root mean square error (RMSE) and the coefficient of determination (R^2). These are defined as:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(P_i - \bar{P})^2}}\right)$$

where O_i is the ith observation, P_i is the ith prediction, $\bar{O}$ is the mean of the observations, $\bar{P}$ is the mean prediction, and n is the total number of observations.

However, care needs to be taken when using such metrics to assess the model predictions for daily N_2O emissions. First, daily N_2O emissions are not statistically independent, so while these metrics are useful for comparing different models, they do not provide an absolute measure of the model error.

In addition, these metrics only assess how well a model predicts the emissions on a given day, while total N_2O emissions over longer periods of time and their response to changing conditions are often of greater interest to most researchers. For example, suppose the model correctly predicted N_2O peaks but these predictions either lead or lag behind the observations by a few days. In this case the model would perform poorly in terms of RMSE and R^2 as a large difference would be observed between the predicted and measured emissions on the peak emission days. However, the model would still be producing reliable estimates of long-term emissions.

The DNDC model can be used to assess the impact of potential greenhouse gas mitigation strategies not only on the targeted gas, but also on crop production and other environmental factors (such as soil C and NO_3^- leaching). Scaling up DNDC from the paddock scale to regional or national scales can be used to compile greenhouse gas emission inventories, identify regions of high emissions and to explore scenarios for the effects of changes in land use or management.

Several problems can arise when scaling up a model developed at the field scale. These include: (a) different processes become important at different scales, (b) the availability of input data, and (c) change of support (i.e. degree of aggregation) for the model input and model output parameters (Heuvelink, 1998).

For regional applications of DNDC, soil data are usually extracted from a GIS or soil survey data in which variability within a cell can be high, and assumptions have to be made about management practices. Many of the model processes are non-linear with respect to the input parameters, and as a consequence setting the soil properties to the mean value over an area may not necessarily produce the mean emission for that area. In addition, the predicted emission rate could vary depending on the size of the averaged area (or resolution). Xu-Ri et al. (2006) examined this effect by comparing model N_2O predictions using 1-km^2 cells, aggregation by soil type, and aggregation over the whole river basin (11,856 km^2). Using the soil type aggregation resulted in predicted N_2O emissions ±11% relative to the predictions using data measured at the 1-km^2 scale (whether the prediction was higher or lower than the base case depended upon the source of the SOC data used). At the whole river basin scale prediction was 64% higher than for the base case. A Monte Carlo simulation using variability information for all the input parameters was able to predict N_2O results within 21% of the 1-km^2 prediction. However, only considering the variability of SOC resulted in an over-prediction of 58%.

The interannual variability of modelled emissions is high as temperature and rainfall events are key drivers of many soil processes. It is therefore advisable to run multi-year simulations to capture the effect of year-to-year variability of temperature and rainfall on greenhouse gas emissions.

By receiving comments and suggestions from a wide range of users worldwide, the DNDC model suite continues to be modified and improved after almost two decades of development. A recent example is a new plan to integrate spatial distribution hydrological models with DNDC to enable it to simulate lateral fluxes of water, N and C to facilitate simulations at watershed or landscape scales.

9. Conclusion

DNDC is a process-based model that simulates the soil biogeochemical processes leading to greenhouse gas emissions from soil. Originally developed to model N_2O emissions and SOC levels in US cropping systems, it has subsequently been adapted to model crop, pasture, rice paddy, and forest systems in a number of countries across the world.

As a process-based model DNDC is a useful tool both for modelling the environmental impacts of agricultural management systems (including feedbacks) and for improving our understanding of the underlying processes. In regional mode, DNDC can be used to develop regional and national inventories and assess the changes in greenhouse gas emissions with expected changes in management and climate. It is also being applied to the development and verification of mitigation strategies as these become available.

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