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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

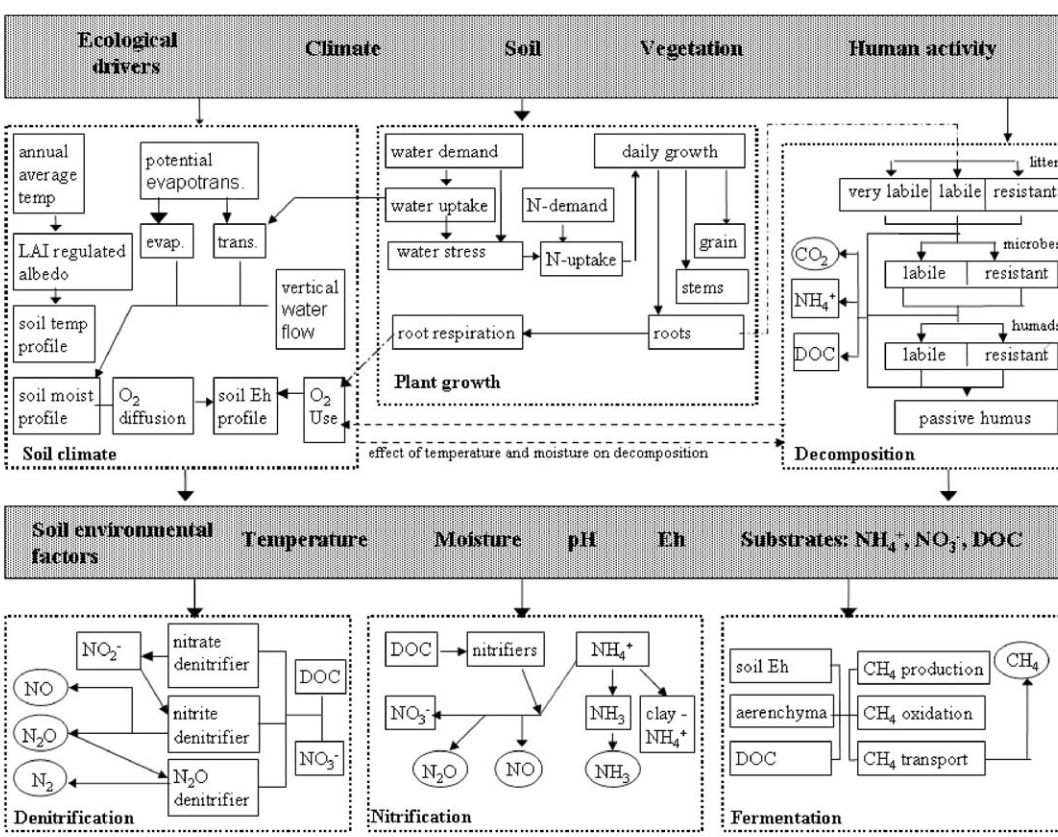

Fig. 1. Schematic diagram of DNDC model structure (adapted from Li, 2000).