Review

First 20 years of DNDC (DeNitrification DeComposition): Model evolution

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A R T I C L E   I N F O

A B S T R A C T

Mathematical models, such as the DNDC (DeNitrification DeComposition) model, are powerful tools that are increasingly being used to examine the potential impacts of management and climate change in agriculture. DNDC can simulate the processes responsible for production, consumption and transport of nitrous oxide (N$_2$O). During the last 20 years DNDC has been modified and adapted by various research groups around the world to suit specific purposes and circumstances. In this paper we review the different versions of the DNDC model including models developed for different ecosystems, e.g. Forest-DNDC, Forest-DNDC-Tropica, regionalised for different areas of the world, e.g. NZ-DNDC, UK-DNDC, modified to suit specific crops, e.g. DNDC-Rice, DNDC-CSW or modularised e.g. Mobile-DNDC, Landscape-DNDC. A 'family tree' and chronological history of the DNDC model is presented, outlining the main features of each version. A literature search was conducted and a survey sent out to c. 1500 model users worldwide to obtain information on the use and development of DNDC. Survey results highlight the many strengths of DNDC including the comparative ease with which the DNDC model can be used and the attractiveness of the graphical user interface. Identified weaknesses could be rectified by providing a more comprehensive user manual, version control and increasing model transparency in collaboration with the Global Research Alliance Modelling Platform (GRAMP), which has much to offer the DNDC user community in terms of promoting the use of DNDC and addressing the deficiencies in the present arrangements for the models' stewardship.

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1. Introduction

Nitrous oxide (N_2O) is a powerful greenhouse gas (GHG) and is also implicated in depletion of the stratospheric ozone layer. Globally, agriculture contributes 60% of the total N_2O emissions (Smith et al., 2007, 2008). Agricultural soils are known to be an important source of N_2O through the processes of nitrification and denitrification and are estimated to contribute 6.1% to anthropogenic global warming (IPCC, 2007). Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrite (NO_2^-) and then nitrate (NO_3^-). Denitrification is the anaerobic microbial reduction of NO_3^- to NO_2^- and then to the gases nitric oxide (NO), N_2O and dinitrogen (N_2).

Mathematical models are powerful tools that are increasingly being used to examine the potential impacts of management and climate change in agriculture. Models can simulate the processes responsible for production, consumption and transport of N_2O (Williams et al., 1992). Models used to establish emissions under current management practices can also be used to compare alternative management scenarios intended to reduce emissions; this capability being more pertinent in a changing climate (Shepherd et al., 2011). Where measurements of emissions cannot easily be obtained, models may be used at the site-scale to interpolate and for nations to extrapolate measurement information, both spatially and temporally, for use in GHG inventories.

The DNDC (DeNitrification DeComposition) model was first described by Li et al. (1992) as a rain event-driven process-orientated simulation model for N_2O, CO_2 and N_2 emissions from agricultural soils in the U.S. The DNDC field scale model coupled decomposition and denitrification processes, as influenced by the soil environment, to predict carbon (C) and nitrogen (N) turnover in agricultural soils. During the past 20 years the original DNDC model, used by researchers throughout the world, has been modified and adapted to include different scenarios and other ecosystems, e.g. forests, wetlands, rice paddies.

Today, the differences and similarities between different DNDC models or versions are neither well-documented nor widely understood, either by the research community or by potential users. To rectify this, the UK has initiated the Global Research Alliance Modelling Platform (GRAMP, (2014); www.gramp.org.uk), using DNDC as a pilot model, with the aim of developing a meaningful, credible model web platform with existing data and prior knowledge. In consort with end-users, every stage will be open to critical review and revision to improve the predictions of soil C and N cycling in the context of climate change. The purpose of this paper is to review the state of the DNDC model to address the issues discussed above by, (1) exploring and describing the main features of different DNDC versions and how they have evolved and are related to each other, (2) assessing information on model use and how the model has been developed to answer questions in ecosystem modelling, and (3) highlighting strengths, weaknesses and potential improvements for the model.

2. Methods

2.1. Literature review of existing DNDC versions and family tree

As part of GRAMP, DNDC model versions have been documented and a model 'family tree' constructed. During this process, model versions were identified using a series of 'biopics'. The biopics were produced as a set of searchable 'card' records summarising versions of the DNDC model that can be used in the DNDC modelling portal as part of the GRAMP system. Using the citations for key papers identified from the biopics, a literature review was carried out and a review of the DNDC family members documented. This information was used to create a 'family tree' and document the chronological development of the DNDC model versions.

2.2. Survey on model use and development

To gather information on important changes to the model and compile information on model use and development, a survey was developed using the online software Quest Back. The survey was circulated to c. 1500 individuals registered to the DNDC Biogeochemistry Model website and global DNDC network. The survey gathered information regarding record keeping of model version

and code changes, data from validation of model versions, collaborations and publications, and the intended use of the model, e.g. impact of land use change or economic analysis. Furthermore, questions were aimed at determining the users understanding of the model processes and the capabilities of the model versions as well as model accuracy and flexibility.

3. Results and discussion

3.1. Literature review of existing DNDC versions and family tree

Since its initial development, numerous changes have been made to the DNDC model by its developers in response to comments and requests from worldwide users aiming to bridge gaps either in functions or regions. Much collaborative work has been carried out with individual research groups to develop country- or need-specific models. Many of these modifications have been incorporated into later versions of the DNDC model

(Giltrap et al., 2010). This continual change in DNDC has resulted in limited documentation existing on the differences between successive updates of the DNDC model and the different versions used by major research groups globally. Due to this, users are unaware of more appropriate versions of the model for their purposes. The successive development of DNDC alongside the development of other versions is described below. Table 1 complements the text descriptions of the model versions with an at-a-glance chronological summary of the main characteristics and developments both within the DNDC model and the different versions of DNDC. Additionally, a schematic family tree of the model versions illustrates the model version development and how the different versions of DNDC are linked to each other (Fig. 1).

3.1.1. DNDC

The DNDC model was first described by Li et al. (1992). The first versions (1.0 – 7.0) of DNDC consisted of three main sub models (Fig. 2) which worked together in simulating N_2O and N_2

Table 1
Chronological development of DNDC versions.

| Publication	Model version	Main functions
Li et al. (1992)	DNDC v. 1.0–7.0	Three submodels: (1) soil-climate/thermal-hydraulic flux, (2) decomposition (three SOC pools), (3) denitrification; no crop growth submodel; nitrification only present as a simple equation.
Li et al. (1994)	DNDC v. 7.1	Four submodels: (1) soil-climate/thermal-hydraulic flux, (2) decomposition (four SOC pools), (3) denitrification; (4) an empirical plant growth submodel.
Li et al. (2000)	PnET-N-DNDC	Predicts emissions of N_2O and NO from forest soils; integrates three existing models: (1) Photosynthesis-Evapotranspiration (PnET) model, (2) DNDC and (3) a nitrification model. New two-component model framework with five submodels: (1) soil-climate/thermal-hydraulic flux, (2) decomposition, (3) denitrification, (4) forest growth in place of crop growth and (5) nitrification. Introduction of 'anaerobic balloon' and the effect of freezing and thawing on soil moisture.
Li (2000); Li et al. (2000)	DNDC v. 8.0	New two-component model framework as developed in PnET-N-DNDC; six submodels: (1) soil-climate/thermal-hydraulic flux, (2) decomposition, (3) denitrification, (4) crop growth (empirical), (5) nitrification and (6) fermentation. Incorporates anaerobic balloon, and the effect of freezing and thawing from PnET-N-DNDC.
Zhang et al. (2002a)	Crop-DNDC	Simulates crop growth through tracking physiological processes along with water and nitrogen stress. Three submodels: (1) soil-climate/thermal-hydraulic flux from DNDC, (2) new phenological crop submodel and (3) decomposition, nitrification, denitrification submodels from Li et al. (1992) integrated into one submodel.
Zhang et al. (2002a)	DNDC v. 8.2	New phenological crop submodel as developed in Crop-DNDC introduced as an add-on as an alternative to the empirical crop growth submodel described in Li et al. (1994).
Zhang et al. (2002b)	Wetland-DNDC	Predicts CO_2 and CH_4 in wetland ecosystems; integrates PnET-N-DNDC, adapted for wetland ecosystems, and the FLATWOODS model; four submodels, (1) hydrological conditions, (2) soil temperature, (3) plant growth and (4) soil C dynamics. Enhanced by Li et al. (2004a) for forested wetland ecosystems. Nernst and Michaelis–Menten equations merged in 'anaerobic balloon'.
Brown et al. (2002)	UK-DNDC	DNDC modified for application to the UK; four submodels: 1) soil-climate/thermal-hydraulic flux, (2) decomposition, (3) denitrification; (4) plant growth. Later updated to the two component, six submodel structure detailed by Cardenas et al. (2013).
Li et al. (2004a)	DNDC v. 8.5	Modification of the 'anaerobic balloon' concept to incorporate not just the Nernst equation but merge the Nernst and Michaelis–Menten equations (from Wetland-DNDC).
Li et al. (2005)	Forest-DNDC	Integration of PnET and DNDC for upland and wetland forested ecosystems; two-component, six submodel structure and functions as in Li (2000); Li et al. (2000).
Saggar et al. (2004)	NZ-DNDC	DNDC adapted for New Zealand conditions; four submodels as in DNDC v. 7.1. Further modified by Saggar et al. (2007) to model an intensive grazed grassland system.
Kiese et al. (2005)	Forest-DNDC-Tropica	PnET-N-DNDC (two components, five submodels) adapted to tropical rainforest ecosystems. Later modified by Werner (2007) and Werner et al. (2006).
Neufeldt et al. (2005)	EFEM-DNDC	GIS-coupled economic-ecosystem model, simulates GHG emissions from typical livestock and crop production systems in Baden-Württemberg, Germany. Coupling of EFEM and DNDC v. 8.0.
Beheydt (2006)	BE-DNDC	Regional framework for calculating N_2O emissions from intensive agricultural land; integration of DNDC v. 8.3P with regional data for Belgium. Further improvements by Beheydt et al. (2007).
Li et al. (2006)	DNDC v. 9.0	Improved simulation of free ammonium dynamics, nitrification, and nitrate leaching.
Leip et al. (2008)	DNDC-Europe	Developed to assess the effect of agri-environmental policy on GHG emissions. Integration of CAPRI and DNDC.
Li et al. (2004b)	DNDC-Rice	DNDC adapted for rice paddy ecosystems. Further refined by Pathak et al. (2005) for the rice paddies of India. Further enhancements and incorporation of MACROS by Fumoto et al. (2008, 2010).
Grote et al. (2009)	Mobile-DNDC	MoBiLE links 1-dimensional biosphere models, e.g. DNDC to get the most appropriate model combination for a particular research task (Grote et al., 2009). MoBiLE-DNDC was subsequently adapted by Wolf et al. (2012)
Smith et al. (2010)	DNDC v. 9.3	Improvement to estimates of soil evaporation.
Kröbel et al. (2011)	DNDC-CSW	Introduction of an empirical submodel to DNDC named the Canadian Spring Wheat (CSW) submodel to allow more accurate estimation of spring wheat growth and N uptake in Canadian agroecosystems.
Haas et al. (2012)	Landscape-DNDC	Designed to simulate multi-ecosystems. DNDC and Forest-DNDC unified into a general soil biogeochemistry module.
Zhang et al. (2012)	NEST-DNDC	Developed to quantify CH_4 fluxes in permafrost conditions. Integration of DNDC with NEST.
Li et al. (2012)	Manure-DNDC	Modification of DNDC to represent the manure life cycle on farms and predict GHG and NH_3 emissions from livestock manure systems.
Li et al. (2012)	DNDC v. 9.4	Shares the same soil NH_3 algorithms as developed in Manure-DNDC.
Li, pers. comm., 2013	DNDC v. 9.5	Improvements in crop growth simulations, hydrological features and other improvements to meet demand for GHG mitigation studies. Most up-to-date version.
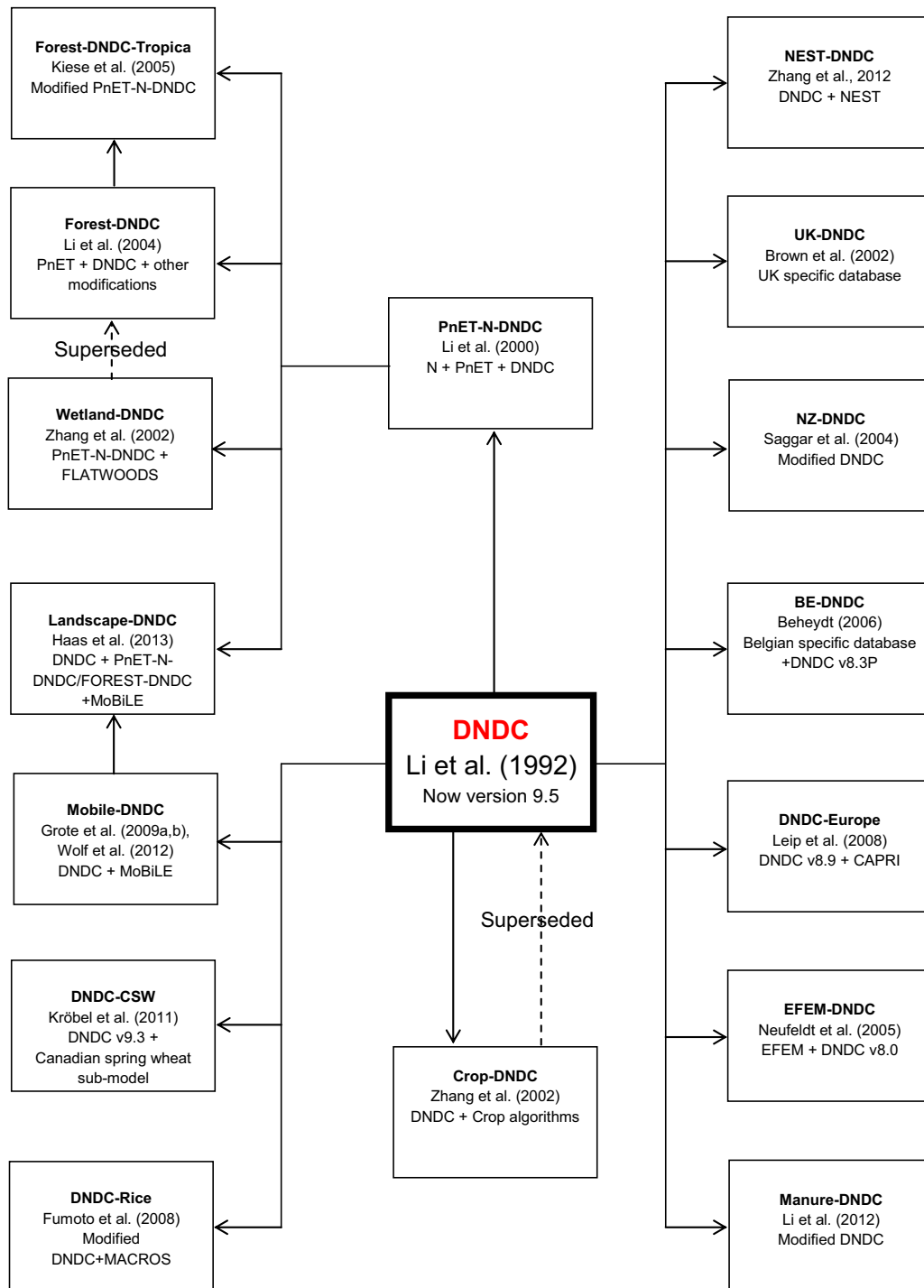
Fig. 1. Schematic diagram of the DNDC extended family.

emissions; (1) soil-climate/thermal-hydraulic flux sub-model, (2) decomposition sub-model, and (3) denitrification sub-model.

During the following two decades many improvements and additions were added to the early version of the DNDC model. In 1994, the model was supplemented with an empirical plant growth sub-model (Li et al., 1994) which contained sub-routines for land cropping practice routines/land management to study the biogeochemistry of soil C in arable land. Later, the DNDC model formed the basis of a new forest model (Section 3.1.2) named PnET-N-DNDC (Li et al., 2000), and many of the developments that were made in producing PnET-N-DNDC were also incorporated into the

DNDC model (Li, 2000), as was the case with many of the stand-alone versions of DNDC that were developed over time.

The DNDC model was further developed to predict methane (CH_4) and ammonia (NH_3) emissions from agricultural ecosystems. Li (2000) explained that in order to construct a process model of soil trace gases, all the factors including ecological drivers, soil environmental variables, and biogeochemical reactions should be integrated into one framework. To this end, Li (2000) adopted the concept of a biogeochemical field, 'a biogeochemical field is an assembly of the spatially and temporally differentiated environmental forces (e.g., temperature, moisture, pH, Eh and substrate
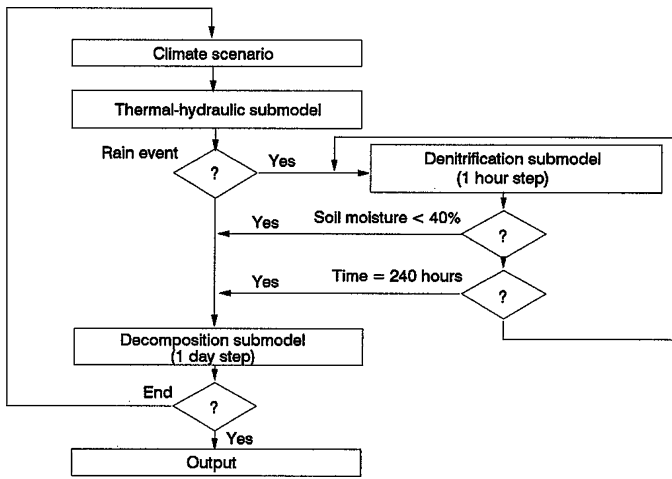
Fig. 2. The structure of the early version of the DNDC model incorporating three submodels (taken from Li et al., 1992).

concentration gradient) that drive biogeochemical reactions in an ecosystem'. The model was reorganised into two components incorporating six sub-models (Fig. 3) and this new structure formed the basis of many DNDC-based models (Table 1). Component 1 linked ecological drivers to soil environmental variables and consisted of the soil climate, crop growth and decomposition sub-models. Component 2 linked soil environmental factors to trace gases and consisted of the already known denitrification sub-

model and furthermore, the two new sub-models for nitrification and fermentation.

The DNDC model (Li, 2000) was further modified by adding several key crop algorithms which were developed as part of Crop-DNDC (Section 3.1.3) to produce a phenological crop growth sub-model. During the development of Wetland-DNDC (Section 3.1.4), Li et al. (2004a) and Li (2007) further developed the concept of the 'anaerobic balloon' that was first introduced in PnET-N-DNDC by merging the Nernst and Michaelis–Menten equations, to form the core of DNDC (DNDC v. 8.5, Table 1), this being possible due to both equations sharing a common factor (oxidant concentration), to track microbial activities.

In more recent years DNDC has formed the basic structure of increasingly more complex modular-based models such as Mobile-DNDC and Landscape-DNDC (Table 1). There are also a number of models that have been developed for different regions of the world, e.g. NZ-DNDC, UK-DNDC, and specific crops, e.g. DNDC-Rice, DNDC-SCW (Table 1). At the same time, many further improvements have been added to the DNDC model itself. In Li et al. (2006), further enhancements were introduced to improve the model capacity for simulating free NH_4^+ dynamics, nitrification, and NO_3^- leaching. A function as described by Steiner (1989) was added to the DNDC model to improve estimates of soil evaporation under different levels of surface residue cover. Recent versions of DNDC share the same soil NH_3 algorithms as Manure-DNDC (Section 3.1.17), described in detail by Li et al. (2012). DNDC has also been improved in simulations of crop growth, and alternative farming management practices such as the use of nitrification inhibitors, slow-release fertilizers, sprinkler and drip irrigation,
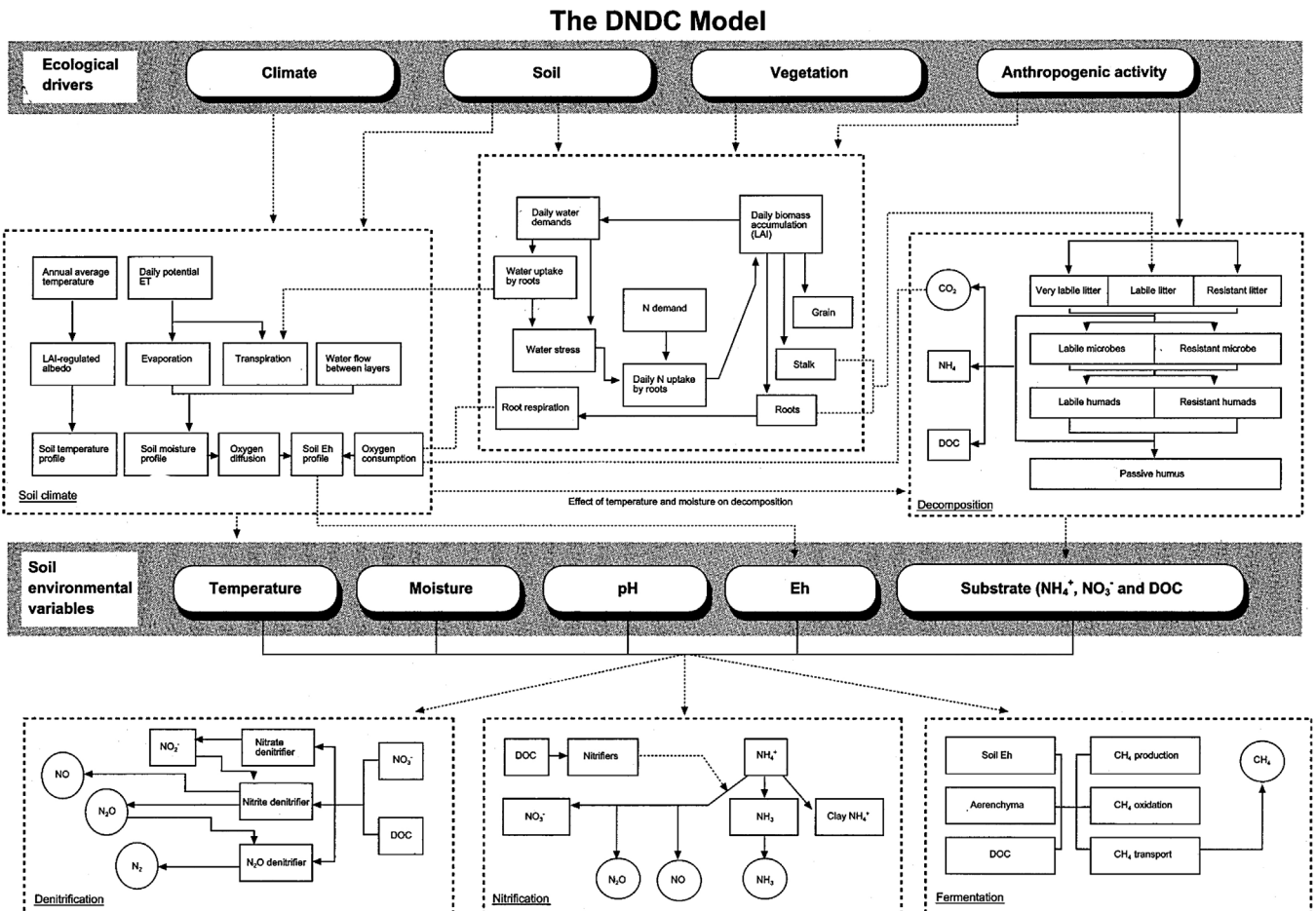

Fig. 3. The two-component DNDC model with six submodels: soil climate, crop growth, decomposition, denitrification, nitrification and fermentation (taken from Li, 2000).

Table 2
Input parameters required by DNDC and default values provided.

Input category	Input	Default values/ options provided?
Location	Site	
	Latitude	
Climate/ weather	Daily mean or max./min. air temperature (°C)	
	Daily precipitation (cm)	
	Daily average wind speed (m/s)	
	Humidity (%)	
	Daily solar radiation (MJ/m^2/day)[a]	✔
	N concentration in precipitation (mg N/l or ppm)	✔
	Atmospheric background CO_2 concentration (ppm)	✔
	Atmospheric background NH_3 concentration (µg N/m^3)	✔
	Annual increase rate of atmospheric CO_2 concentration (ppm/year)	✔
Soil	Land use type[b]	✔
	Soil texture[c]	✔
	Bulk density (g/cm^3)	
	pH	
	SOC at surface (kg C/kg soil)	
	SOC partitioning (fraction & C/N ratio of litter, humads, humus and char C)	✔
	SOC profile: depth of top soil with uniform SOC content (m); SOC decrease rate below topsoil (0.5–5)	✔
	Clay fraction (0–1)	✔
	Soil structure: Bypass flow rate (0–1); depth of water retention layer (m); drainage efficiency (0–1)	✔
	NO_3^- concentration at surface soil (mg/kg)	✔
	NH_4^+ concentration at surface soil (mg/kg)	✔
	Field capacity (WFPS; 0–1)	✔
	Wilting point (WFPS; 0–1)	✔
	Porosity (0–1)	✔
	Hydro-conductivity (m/hr)	✔
	Microbial activity index (0–1)	✔
	Slope (0–90°)	✔
	Soil salinity index (0–100)	✔
	Rainwater collection index (0–1)	✔
	Use SCS and MUSLE functions (yes/no)	
Farming management practices		
Crop	Type (62 default types)	✔
	Crop rotation (no. crops per year)	
	Planting and harvest date	
	Cover crop (yes/no)	
	Perennial crop (yes/no)	
	Fraction of leaves & stems left in field after harvest (0–1)	✔
	Annual N demand (kg N/ha/year)	✔
	C/N ratio of grain, leaf, stem & root	✔
	Biomass fraction of grain, leaf, stem & root (0–1)	✔
	Maximum biomass production (kg/C/ha/year)	✔
	Thermal degree days for maturity (days)	✔
	Water demand (g water/g dry matter)	✔
	Optimum temperature for crop growth (°C)	✔
	N fixation index (crop N/N from soil)	✔
	Vascularity index for wetland plants (0–1)	✔
Fertiliser	Type, method, rate, no. of applications, dates, depth	
Manure	Type, method, rate, no. of applications, dates, depth	
	C/N ratio of manure	✔
Tillage	Method, no. of applications, dates	
Grazing or cutting	No. of grazing/cutting applications, dates; grazing livestock type, grazing hours per day & stocking rate	
Irrigation	Method, rate, no. of applications, dates	

Table 2 (Continued)

Input category	Input	Default values/ options provided?
Flooding	Method, dates, N in flood water, water leaking rate	
Plastic	No. of plastic (mulch/greenhouse) applications, dates, % of plastic coverage	

[a] Default values are calculated, based on latitude, when measured solar radiation data are not available.
[b] Upland crop field, rice paddy field, moist grassland/pasture, dry grassland/pasture, wetland, tree plantation.
[c] Sand, loamy sand, sandy loam, silt loam, loam, sandy clay loam, silty clay loam, clay loam, sandy clay, silty clay, clay, organic soil.

plastic film mulching etc. to meet the demand for GHG mitigation studies. Two basic hydrological features were added to DNDC to enhance its capacity for modelling surface runoff and soil erosion (Deng et al., 2011). At the date of writing this paper (June 2014), the latest version of DNDC is 9.5.

3.1.1.1. Input parameters. DNDC can be run in two modes; site or regional. The main input parameters required by DNDC and thus DNDC-based models are summarised in Table 2. The mandatory input parameters for which defaults are not provided are location (latitude), weather data (a minimum of daily mean air temperature and precipitation), soil bulk density, pH and SOC at the surface (0–10 cm). Input of these parameters alongside selecting the appropriate land use and crop type, soil texture and farm management practices, to best suit the modelling situation, will provide sufficient detail to run the model although there are many parameters that can and should be user-defined. When DNDC is used for regional estimates of trace gas emissions, the model needs the spatially and temporally differentiated input data stored in geographic information system (GIS)-type databases in advance.

3.1.1.2. Output parameters. Output parameters provided DNDC model runs are detailed in Table 3 and include daily reports on weather, soil climate, soil C and N pools/fluxes, crop growth, and field management. In addition to daily reports, DNDC produces an annual report at the end of each simulated year to summarise the crop growth/yield, soil C and N pools/fluxes and water balance for the simulated site. When a multi-year simulation is conducted, a multi-year result file is produced by DNDC enabling an at-a-glance review of the major annual pools or fluxes across the simulated years. Outputs from regional runs are recorded as geographically explicit data in a GIS database.

3.1.1.3. Model validation. Model validation against measured experimental data is an essential process in the development of any model to ensure model accuracy. From the literature, measured data commonly used for model validation include: (1) crop yield and biomass; (2) soil: temperature, moisture, organic carbon, NH_4^+, NO_3^- and water-filled pore space (WFPS); and (3) fluxes of CO_2, N_2O, NO, NH_3 and CH_4 from the soil–plant system. Details of validation data used for a variety of DNDC-based models are summarised in Giltrap et al. (2010).

3.1.2. PnET-N-DNDC

PnET-DNDC is a forest model and integrates three existing models, namely, DNDC, the photosynthesis-evapotranspiration (PnET) model (a forest physiology model), and a nitrification model (developed for prediction of nitrifier growth/death rates, nitrification rate and nitrification-induced NO and N_2O production (Li et al., 2000; Stange et al., 2000).

Table 3
Output parameters provided by DNDC.

Output category	Output
Climate/weather	Air temperature (°C) Precipitation (cm) Solar radiation (MJ/m²/day) Wind speed (m/s) Humidity (%) Potential/actual evapotranspiration (mm/day) Actual evaporation/transpiration (mm/day)
Crop	Crop leaf/stem/root/grain biomass (kg C/ha) Crop accumulative temperature (°C) Crop growth/leaf area indexCrop water demand (mm/day) Daily crop water stress (0–1) Crop N demand (kg N/day) Crop N taken from soil/N dry deposition/biological N fixation (kg N/ha/day) Daily N stressDaily increment of crop N and crop leaf/stem/root/grain N (kg N/ha/day) Daily increment of crop biomass/root biomass/grain biomass/ crop leaf and stem (kg C/ha) Crop accumulative N content (kg N/ha) Daily crop shoot/root/grain senescence (kg C/ha)
Farming management practices	Daily irrigation water (mm/day) Daily N/P fertiliser/manure application rate (kg/N or P/ha) Daily plant cut (kg C/ha)
Livestock	Grass shoot biomass (kg C/ha) Dairy cow/beef cow/swine/sheep/goat/horse population (head) Hours animal spends grazing per dayDaily grazed biomass (kg C and N/ha) Daily production of faeces/urine (kg C and N/ha) Daily feed deficit
Soil climate	Soil temperature profile (°C) Soil moisture profile (water-filled porosity) Soil oxygen content profile (kg O_2/layer) Soil redox potential profile (mV) Water table (mm, minus is below soil surface) Soil ice content (WFPS) Soil profile (0–50 cm) ice content (mm) Snow pack (mm water) Total water content in soil profile (0–50 cm)/water content below 50 cm (mm) Soil pH
Soil C	Soil very labile litter/labile litter/resistant litter/humads/humus content (kg C/ha) Soil living microbial/total organic C/dissolved organic C content (kg C/ha) Daily change in SOC content (kg C/ha/day) Plant photosynthesis rate (kg C/ha/day) Plant shoot autotrophic/root autotrophic/ soil heterotrophic respiration rate/ecosystem respiration rate (kg C/ha/day) Plant net primary production rate (kg C/ha/day) Net ecosystem C exchange rate (kg C/ha/day) Plant stubs standing on ground (kg C/ha)DOC available for methanogens/methane content in soil profile (kg C/ha) Daily methane production/oxidation/flux (kg C/ha/day) Daily DOC loss through leaching flow (kg C/ha/day) Daily litter/manure incorporation (kg C/ha/day)
Soil N	Daily crop N uptake (kg N/ha) Soil urea/ammonium/nitrate/exchangeable ammonium/ammonia content in soil profile (kg N/ha) Daily nitrous oxide/nitric oxide/dinitrogen/ammonia emission rate (kg N/ha/day) Daily nitrate/urea loss through leaching flow (kg N/ha/day) Daily gross N/ net N mineralisation rate (kg N/ha/day)DOC/available N/N_2O/N_2 trapped in soil ice (kg C or N/ha) Daily nitrification/denitrification/soil N fixation/litter incorporation rate (kg N/ha/day)
Soil P	Organic/labile inorganic/adsorbed/complex phosphorus content in soil profile (kg P/ha) Daily crop demand/crop uptake for P (kg P/ha/day) Crop P content (kg P/ha) Daily P loss through leaching flow (kg P/ha/day)
Soil water	Daily initial soil water content/soil water content at end of each day (mm) Soil liquid water/ice water content/daily initial and end soil water content below 50 cm (mm) Daily precipitation/irrigation (mm/day) Ponding water on soil surface/snow pack water content (mm) Daily soil water loss through evaporation/transpiration/ponding water evaporation/subsurface leaching (mm/day) Daily water loss through surface runoffDaily change in soil water storage in profile (mm/day) Daily total water influx/efflux to/from soil (mm/day) Error in water balance (mm/ day) Daily soil erosion rate (kg/day) Daily SOC/soil inorganic N/organic P/adsorbed P/labile P loss due to soil erosion (kg C/day)

Due to the creation of the 'anaerobic balloon' concept, PnET-N-DNDC is able to model soils where aerobic and anaerobic microsites exist simultaneously, as it can predict both nitrification and denitrification in the soil at the same time (Li et al., 2000). The DNDC two-component framework (Fig. 3) is employed in PnET-DNDC and the structures and functions of the sub-models basically remain as they were in the parent models (further description of these models are given by Li et al. (1992, 1994) and Aber et al. (1996)). Many new features and algorithms were added to PnET-N-DNDC to account for the effect of forest ecosystems including an additional pathway, chemodenitrification, for the production of NO (which only occurs in the acidic soils commonly found in many temperate forests and most tropical forests (Li et al., 2000)). PnET-N-DNDC has since been integrated with Wetland-DNDC to produce Forest-DNDC (Giltrap et al., 2010).

3.1.3. Crop-DNDC

Crop-DNDC integrates detailed crop growth algorithms (Zhang et al., 2002a) with DNDC to simulate C, N and water cycles. Crop-DNDC was developed at the Canada Centre for Remote Sensing, Ottawa (Zhang et al., 2002a) and uses three interacting sub-models to simulate crop growth through tracking physiological processes (such as phenology, leaf area index, photosynthesis, respiration, assimilate allocation, rooting processes and N uptake) along with water stress and N stress.

Since the model is able to simulate crop yields, soil C sequestration and trace gas emissions it can potentially be used for predicting the impacts of alternative management strategies or climate change on agricultural production and environmental safety (Zhang et al., 2002a). The new algorithms introduced to the crop sub-model (Zhang et al., 2002a) act as an alternative approach to the empirical crop growth sub-model employed in DNDC (Li et al., 1994). However, the empirical crop submodel is ordinarily used and thus Crop-DNDC has been superseded by DNDC (Fig. 1).

3.1.4. Wetland-DNDC

Wetland-DNDC was developed by integrating two existing models, namely, PnET-N-DNDC and FLATWOODS (Sun et al., 1998), a distributed hydrological model, to predict CO_2 and CH_4 emissions driven by hydrology, soil biochemistry and vegetation processes in wetland ecosystems (Zhang et al., 2002b).

Zhang et al. (2002b) describes the model as consisting of four interacting sub-models which simulate water table dynamics, soil temperature, plant growth of wetland species and the anaerobic effects found in wetlands (Zhang et al., 2002b). The original version of Wetland-DNDC, described above, focused on natural wetlands with few management options. A modified version of Wetland-DNDC included enhancements by Li et al. (2004a) to enable changes in management practices that affect C sequestration to be represented, such as forest harvest, tree planting, chopping and burning and water management. An important change was made to quantify redox potential dynamics and its impacts on N_2O and CH_4 production. Li et al. (2004a) modified the 'anaerobic balloon' concept to incorporate not just the Nernst equation but merge the Nernst and Michaelis–Menten equations, this concept was later embedded and formed the core of the DNDC model.

Most of the wetland hydrological features existing in Wetland-DNDC have been incorporated in either DNDC or Forest-DNDC, as an independent model. As a consequence, Wetland-DNDC has been phased out (Fig. 3).

3.1.5. UK-DNDC

DNDC was modified for application into the UK to produce UK-DNDC (Brown et al., 2002). The original UK-DNDC model contained four sub models based on Li et al. (1992) and Li (2000). UK-specific input data were added to DNDC's database to include soil characteristics, crop types, climate, livestock, and farming practices. During 2006–2011 a windows version of UK-DNDC was developed and a spatially differentiated manure application database was created and linked to UK-DNDC; this made UK-

DNDC unique for modelling the pasture-dominated agro-ecosystems in the UK.

Whilst the above improvements were made to UK-DNDC, in the meantime, much progress was made in DNDC regarding crop growth, soil climate and soil C and N dynamics, which substantially enhanced the model's capacity. This resulted in differences between UK-DNDC and DNDC regarding their performances. Thus, a 'new' UK-DNDC model was created to combine the advantages of the original UK-DNDC with the current version of DNDC at that time (DNDC version 9.4, September 2011). The new version of UK-DNDC adopted most of the latest developments in DNDC detailed in Li (2000) and Li et al. (2000) including improved simulations of (1) crop growth, (2) farming management practices, (3) soil climate, (4) NH_3 volatilisation from soil, fertilizer and manure applications, (5) NO_3^- leaching loss, (6) gaseous N emissions from nitrification and denitrification, and (7) CH_4 emissions from fermentation. At the regional scale, the new UK-DNDC utilised its own databases including the spatially differentiated (regional) livestock numbers and their daily manure production. Information on the databases and structure of UK-DNDC is detailed in Cardenas et al. (2013). The UK-DNDC model has recently been modified by further parameterization of the grazing systems to better simulate the effect of grazing on N_2O production (Wang et al., 2012).

3.1.6. Forest-DNDC

Forest-DNDC is a model for predicting forest production, soil C sequestration, and trace gas emissions in upland and wetland forested ecosystems (Li et al., 2005). In common with PnET-DNDC and the later Wetland-DNDC, the core of Forest-DNDC was constructed by integrating PnET, a forest physiological model developed by Aber et al. (1996), with DNDC. The integration created a new modelling framework to fill some gaps existing in most forest models in terms of the linkage between forest and soil processes. Major management practices, such as deforestation, reforestation, thinning, burning, drainage, wetland restoration, fertilisation etc., were parameterised and linked to the plant-soil processes as applied in the modified Wetland-DNDC model(Li et al., 2004a). Equipped with these functions, Forest-DNDC is capable of simulating C and N cycles for both wetland and upland forest ecosystems.

3.1.7. NZ-DNDC

NZ-DNDC is a modified version of DNDC that includes a number of alterations to best reflect the conditions found in New Zealand and was developed by Saggar et al. (2004). The presence of distinctive and diverse soil types within a short distance and soils having a higher organic C content than the world average; coupled with climatic conditions and grazed pastoral systems (grazing 24 h a day) which differ from many other countries meant that the application of the DNDC model to New Zealand was challenging. NZ-DNDC was based on an early version of DNDC and comprised four sub-models to simulate soil-climate, crop growth, decomposition, and denitrification. Several modifications were made to the model to allow for southern hemisphere conditions (Saggar et al., 2004). NZ-DNDC was further modified by Saggar et al. (2007) to model the entire suite of the interactions among plants, soil, atmosphere and management in an intensive grazed grassland system. The major modifications were related to pasture crop growth, N input from animals, evapotranspiration and soil moisture regime.

3.1.8. Forest-DNDC Tropica

PnET-N-DNDC was modified by Kiese et al. (2005) to produce reliable estimates of N_2O emissions from tropical rainforest ecosystems. Due to principal differences in forest growth and soil hydrological properties between tropical and temperate regions,

Kiese et al. (2005) modified the parameterisation of the original PnET-N-DNDC model to a 'tropical version', keeping the general structure of the original model. The physiological parameters for the rainforest were based on the 'Evergreen Broadleaf Forest' parameterisation used in the BIOME-BGC model (Hunt et al., 1996), but also on the authors' own measurements (Kiese and Butterbach-Bahl, 2002; Kiese et al., 2003).

The Forest-DNDC-Tropica model developed by Kiese et al. (2005) was modified further by Werner (2007) and Werner et al. (2006). Compared to the original Forest-DNDC-Tropica model, three important model sections were improved (Werner, 2007). First, the distribution of SOC in the soil profile was revised. Pedo-transfer functions (vital for simulating soil hydrology) were added to the model and model internalisation of wood mass, leaf mass and floor mass were removed from the model, due to it being specifically calibrated for tropical rainforest ecosystems, and have now become external model input parameters (Werner et al., 2006).

3.1.9. EFEM-DNDC

EFEM-DNDC is a GIS-coupled economic-ecosystem model, which simulates GHG emissions from typical livestock and crop production systems in Baden-Württemberg, Germany. The model is a coupling of the Economic Farm, Emission Model (EFEM) (Angenendt, 2003) and the DNDC model. The EFEM model simulates farm emissions of CO_2, CH_4, N_2O, and NH_3 from fossil fuels, mineral fertilisers, additional feed, ruminant enteric fermentation, and manure management, and provides economic parameters, such as gross margin, shadow prices, and mitigation costs (Neufeldt et al., 2005).

Coupling the economic farm production model EFEM with DNDC allows for a realistic simulation of disaggregated soil, production system, and regional GHG emissions from agricultural systems. GHG mitigation measures applied at regional scale can be evaluated in terms of their environmental and economic credentials through the development of scenarios for the EFEM-DNDC model (Neufeldt et al., 2005).

3.1.10. BE-DNDC

A regional framework for calculating N_2O emissions from intensive agricultural land (croplands and temporary grasslands) was developed by integration of the DNDC model (version 8.3P) with regional data on soil and climate, land use and farm practices for Belgium (Beheydt, 2006). The regional predictions of N_2O emissions were based on regression equations developed separately for cropland and grassland that scaled the DNDC model outputs. The regression equations were corrected for the differences between simulated and measured emissions at 22 long-term field monitoring sites in Belgium (Beheydt et al., 2007). To represent uncertainty in model inputs, the framework calculated emissions with high and low estimates of soil C content.

3.1.11. DNDC-Europe

The DNDC-Europe model was developed to assess the effect of agri-environmental policy on GHG emissions (Leip et al., 2008). The large scale economic model for agriculture, CAPRI (Common Agricultural Policy Regional Impact Assessment) detailed in Britz (2005), was integrated with DNDC to produce European simulations of GHG emissions, C stock exchanges and N budgets of soils. The CAPRI framework was developed to capture the complex interaction between the agricultural market, environmental policy, trade systems and the economic behaviours of farmers, consumers and processors at a regional scale and then provide a policy impact assessment on a global scale. The integrated DNDC-Europe modelling framework allows environmental impacts such as

GHG emissions to be analysed in the context of economic and social indicators provided by the CAPRI model.

3.1.12. DNDC-Rice

The DNDC model was first adapted to simulate GHG emissions from rice paddy ecosystems by Li et al. (2004b). The revised model used the 'anaerobic balloon' concept to model soil biogeochemistry under the anaerobic conditions found in paddy rice-involved agro-ecosystems. To model rice (and other crop) development and growth, a generic crop model, Modules of an Annual CROp Simulator (MACROS), developed by Penning de Vries et al. (1989) was modified and integrated with DNDC. Pathak et al. (2005) and Babu et al. (2006) further refined the DNDC model developed by Li et al. (2004b) to simulate emissions of CO_2, CH_4, and N_2O under the conditions found in the rice paddies of India.

Fumoto et al. (2008, 2010) published research using the DNDC adaptation which was by now labelled as DNDC-Rice. Fumoto et al. (2008, 2010) enhanced DNDC's capacity on modelling paddy biogeochemistry by refining the CO_2-induced and DOC-induced CH_4 productions. The enhancements carried out by Fumoto et al. (2008) allowed DNDC to improve its performance in predicting CH_4 emission from rice fields across a range of climatic, soil, and management scenarios. Fumoto et al. (2010) used the modified DNDC-Rice to assess the CH_4 mitigation potentials of alternative water regimes in rice fields in Japan.

3.1.13. Mobile-DNDC

MoBiLE (Modular Biosphere Simulation Environment) is a framework to link 1-dimensional biosphere models such as DNDC in order to get the most appropriate model combination for a particular research task (Grote et al., 2009). The framework allows efficient selection, initialization, and running of models that focus on one or more aspects of the biosphere. Within the framework, the models are treated as modules that can be combined with any other module according to a specific task.

Many models have been incorporated into the MoBiLE framework, e.g. Grote et al. (2011) integrated PSIM, a physiology based model which simulates vegetation processes, with DNDC to enable a detailed view and characterisation of C fluxes and pools within forest ecosystems. This version of the application of DNDC is often referred to as MoBiLE-DNDC and offers an alternative to the PnET-N-DNDC implementation within the MoBiLE framework. MoBiLE-DNDC was subsequently adapted by Wolf et al. (2012) to examine N_2O emissions during freeze–thaw events in temperate ecosystems, through the addition of routines that relate maximum snow height to end of season biomass.

3.1.14. DNDC-CSW

Kröbel et al. (2011) introduced a new empirical sub-model to DNDC named the Canadian Spring Wheat (CSW) sub-model (DNDC-CSW) to allow more accurate estimation of spring wheat growth and N uptake in Canadian agroecosystems. The sub-model was added as a stand-alone section to the DNDC source code (alongside the existing crop growth model).

3.1.15. Landscape-DNDC

Landscape-DNDC is a direct descendent of the MoBiLE model framework (Grote et al., 2009; Fig. 1) and is capable of simulation of soil GHG exchange of forest, arable and grassland systems. Landscape-DNDC unifies DNDC and Forest-DNDC into a general soil biogeochemistry module to allow Landscape-DNDC to simulate ecosystem C and N turnover and changes in soil C and N stocks for various land use types and periods of land use change (Haas et al., 2013). A DNDC-based physiology module for agricultural crop growth (including grassland) and a PnET-based forest growth module allow land use change in a transient way to

be described (Haas et al., 2013). Modules, derived from physical and chemical principles that describe soil environmental conditions, soil-chemistry integrating microbial C and N turnover processes and vegetation dynamics are integrated within the model (Rahn et al., 2012). The model can be applied at site scale and three-dimensional region simulations.

3.1.16. NEST-DNDC

NEST-DNDC was developed to quantify CH_4 fluxes in permafrost conditions. The model simulates the biophysical and biogeochemical processes in plant communities and up-scales them to the ecosystem scale based on the areal fractions of the plant communities in the ecosystem (Zhang et al., 2012). NEST-DNDC was created by integrating DNDC with a permafrost model, the Northern Ecosystem Soil Temperature (NEST) model (Zhang et al., 2003) and is capable of modelling the interactions between soil thermal-hydrological conditions and biogeochemical processes in permafrost soils (Zhang et al., 2012). NEST-DNDC is also able to simulate upland and wetland ecosystems without permafrost. The modelled soil profile can contain many different soil textures and layers of varying thickness and gravel content. The model can be applied to a wide range of ecosystems from forest to tundra, as it can model an upper and understory of woody plants, a layer of sedges or grass and a layer of mosses.

3.1.17. Manure-DNDC

To respond to the increasing demand for tools to quantify GHG and NH_3 emissions from livestock operations, Li et al., 2012 developed the Manure-DNDC model. Manure-DNDC incorporates a matrix of biogeochemical reactions into a computable framework, for representing the manure life cycle on farms, to predict GHG and NH_3 emissions from livestock manure systems. In consideration of similarities between the manure organic matter and the soil organic matter, the biogeochemical processes of soil organic matter developed in DNDC have been fully adopted to describe the manure organic matter turnover in Manure-DNDC. The relations between environmental factors and biogeochemical reactions are used in order to estimate CO_2, N_2O, CH_4 and NH_3 emissions from the farm component facilities.

All of the biogeochemical reactions (decomposition, urea hydrolysis and NH_3 volatilisation, nitrification, denitrification, fermentation) in DNDC were inherited in the new Manure-DNDC model by linking them to the manure lifecycle across the feedlot, compost, lagoon, anaerobic digester and field application at the
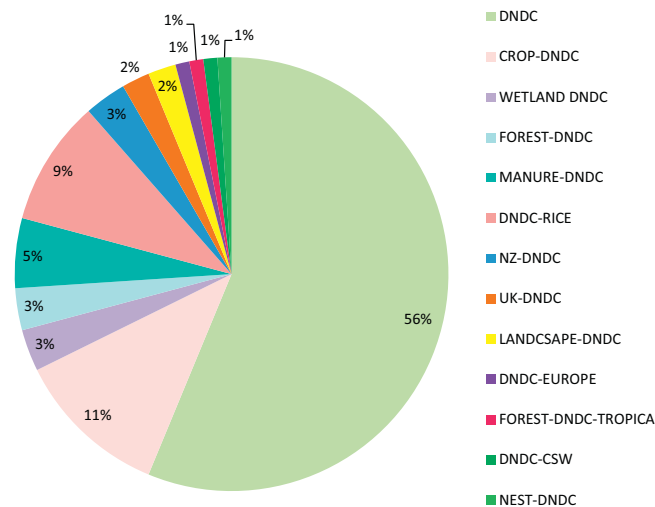

Fig. 4. Percentage of survey respondents using each version of DNDC.

farm scale (Li et al., 2012). Each of the components on a farm where manure is stored and emissions emanate can be selected and integrated in the model to describe the facilities on any given farm. The model can be applied to a variety of livestock facilities as well as cultivated soils.

4. Survey on DNDC model use and development

There were 98 respondents to the GRAMP survey, the majority of which (44%) were located in Asia, with Europe and North America accounting for 23% and 22% of respondents, respectively. The remainder of respondents were distributed more or less equally (3–5%) between Africa, Australia and New Zealand and South America. The findings of the survey showed that the DNDC model is the most commonly used of all the model variants (56% of all survey respondents; Fig. 4) and thus the results of the survey concentrate primarily on the DNDC model. From the results of the survey, strengths and weaknesses of DNDC were recognised (Sections 4.1 and 4.2); recommendations for addressing the issues identified (Section 4.3), the way forward for DNDC (Section 4.4) and opportunities for wider use of the DNDC model (Section 4.5) have been discussed.

4.1. Strengths

Survey respondents identified the comparative ease with which the DNDC model can be used and the attractiveness of the graphical user interface as the key features largely responsible for its widespread use. The comprehensive library of default settings for 62 crops and 12 soil types enables users to model a wide range of sites and situations without the need for considerable amounts of rarely measured input data. Furthermore, many of these inputs can also be user-defined to accommodate a greater range of possibilities. The output of the model is equally comprehensive and detailed, with the majority of parameters reported on a daily time step. Thus, DNDC offers users considerable flexibility, not only in the nature of the situations modelled, but also for the output available for evaluation. Another strength deserving of recognition is the willingness of the DNDC model developer, to collaborate with users for the purpose of using and improving the model and its performance. The major uses to which DNDC-based models are deployed are the estimation of N_2O emissions at a regional or national scale (41% of survey respondents) and assessing the potential impacts of land use change (54% of survey respondents).

4.2. Weaknesses

Paradoxically, some of the strengths identified above could also be considered to be weaknesses. More than half (56%) of survey respondents had been using DNDC models for less than one year, and only 8% of respondents had used DNDC models for five or more years. It is therefore likely that the user community contains many inexperienced modellers, which may have some bearing on the reported quality of modelling achievable with DNDC-based models. As with the advent of drop-down menus in statistical analysis software, a user-friendly model may well be deployed by users with insufficient understanding of the suitability of the model and the modelling process for their intended purposes. This situation is simultaneously exacerbated and reinforced by the fact that the manual for DNDC concentrates on the functional use of the model, i.e. how to set up and run input files, at the expense of technical/scientific information about the model and its use. Many survey respondents highlighted the need for improvements to the instruction manual including a good description of the processes behind DNDC and detailed descriptions of the input and output parameters. This problem is not limited to DNDC, e.g. users of

Landscape-DNDC report similar problems in finding solutions to problems through the instruction manual. Over 77% of survey respondents rated their understanding of the DNDC-based model they were using as neutral, poor or very poor. A comprehensive user manual would also increase the transparency of the model, which was rated as neutral, poor or very poor by 70% of respondents. Given DNDC's acknowledged strength in the modelling of N_2O emissions, the need for a comprehensive manual is further justified when 46% of respondents rate their understanding of how the model calculates N_2O emissions as either neutral, poor or very poor.

Despite DNDC-based models being frequently used to calculate GHG emissions, in common with similar biogeochemical process models (Frolking et al., 1998), the predictions of N_2O emissions from organic manures and in the absence of any additional N fertilisation are often too low (e.g. Abdalla et al., 2009). For the minority (6%) of survey respondents who gave an indication of their confidence in DNDC's predicted N_2O emissions in the absence of additional N fertilisers, only half had confidence in the output. Inaccuracies in estimation of N_2O emissions for frozen soils have also been highlighted in several papers and by survey respondents (e.g. De Bruijn et al., 2009; Kim et al., 2012), but has been in part addressed by the modifications documented in Kariyapperuma et al. (2011).

Other weaknesses highlighted by survey respondents included not having access to the DNDC source code and lack of version management making it very difficult to understand why changes have been made to the code and their impact. There are also issues with availability of input parameters for specific situations, e.g. one survey respondent stated that the model parameters of Forest-DNDC-Tropica are lacking specificity for wider application in the tropics. A lack of measured data available to validate models was also seen as a weakness, e.g. DNDC and Crop-DNDC. Protocols or standard operating procedures for calibration, validation, statistical evaluation of fit and general testing of DNDC were requested by 46% of survey respondents and would benefit the 68% of respondents who were comparing the models' output with field measurements (predominantly crop yield, N_2O emissions, soil C sequestration and soil water) and the 41% of respondents performing assessments of sensitivity and uncertainty as part of their modelling work.

4.3. Recommendations for addressing the issues identified in the survey

GRAMP has the potential to address many of the weaknesses described above in order to improve the user experience for current and potential model users alike. In the first instance this will be most beneficial to users of the piloted DNDC model, but with time this capability will extend to users of other DNDC-based models as the GRAMP platform expands. GRAMP aims to foster a membership which includes a mix of novice and experienced users and researchers with considerable modelling expertise capable of producing transparent documentation, specifically a comprehensive user manual, such as that available for CoupModel (CoupModel, 2014; http://www2.lwr.kth.se/Vara%20Datorprogram/CoupModel/index.htm).

Support through a series of on-line tutorials (as used in Coup) could be provided, which would also include an initial orientation and familiarisation tutorial. General testing by itself could be supported further by the provision of datasets and numerical databases through the GRAMP website. In addition to the training of less experienced users, GRAMP will provide an efficient means of co-ordinating further testing of the initially the DNDC model by experienced modellers which can then be extended to other DNDC-based models.

4.4. The way forward for DNDC

From the literature it is clear that many modifications have been made to DNDC over the last 20 years to meet the needs of the user. Modifications that have been made by users of predominantly variants of DNDC, but would also benefit the users of DNDC include:

1. Modularization of code structure (Haas et al., 2013).
2. Development of an integral optimisation function for crop and other input parameters (Lamers et al., 2007; van Oijen et al., 2011).
3. Incorporation of economic analysis (proposed, but not yet implemented by Li et al., 2012).

Other improvements for consideration, as suggested through the GRAMP survey include:

- Addition of an integral "score sheet" to test the accuracy of the model output, relative to field measurements, using a standardised approach. It has been noted that too many published papers describe the agreement between modelled and measured values as "good" without reference to any statistical assessment of fit.
- A tailored output option for national GHG inventories.
- For advanced users, greater access to the code so that the way in which the model represents processes can be changed.
- Extension of the model's output to include DOC in ground water. This output would be of interest to those responsible for public supplies of drinking water and to those evaluating the environmental impacts of land use change such as wind-farm establishment on peatlands.

4.5. Opportunities for wider use

To date, DNDC-based models have been predominantly used to inform the research community (identified as the end-user by 57% of survey respondents), rather than government/policy makers (32%). Through the provision of documentation and training resources GRAMP would be able to increase the accessibility of the model, to support its use by a wider audience and to promote good modelling practice.

The breadth of output provided by DNDC means that the model has yet to reach its potential in terms of application, and like other biogeochemical process models could find extensive use in modelling parameters other than N_2O. Other, more applied uses of DNDC, could be supported by the GRAMP via a series of advice notes on subjects such as the statistical assessment of fit, gap-filling of datasets, field experiment design and the identification of parameters for measurement and data exploration in order to gain insight into responses observed in the field. Similar to this study, other models that are widely used can be analysed in terms of their history (evolution), uses and performance. This, together with validation using experimental datasets will provide confidence in their use to fill gaps and test scenarios.

5. Concluding remarks

Throughout its 20 year history, the DNDC model has undergone many changes and its on-going value to the scientific community is reflected in the number of current users, the vast literature base and the array of model versions of DNDC. However, in common with all biogeochemical process models, the DNDC model has both strengths and weaknesses. GRAMP has much to offer the DNDC user community in terms of promoting the use of DNDC and addressing the deficiencies in the present arrangements for the model's stewardship.

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