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Review

The development of the DNDC plant growth sub-model and the application of DNDC in agriculture: A review

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ABSTRACT

Plant growth plays an important role in regulating soil C and N as well as water regimes and can therefore influence soil biochemical or geochemical processes. A sub-model was built in DNDC (DeNitrification-DeComposition) to simulate crop growth; since its development, it has often been modified and adapted to suit specific purposes, crops and circumstances. Here, we review the chronological history of various versions of the DNDC plant growth sub-models and present the results of a literature search regarding the application of the DNDC model to various crops in agriculture. We found that food, oil and sugar crops were the primary research focus and accounted for 67.5%, 12.5% and 6.3% of all DNDC crop-based studies, respectively. We also summarize the research achievements published in recent years, and conclude that the DNDC plant growth sub-model could be successfully used to assist in predicting trace gas emissions and soil carbon and nitrogen dynamics after modifying some of the parameters obtained from relevant literature to suit local cultivars. The objective of this study is to provide DNDC users with an understanding of the model mechanisms related to field and horticultural crops, with suggestions for modelling different crops and outlining further model applications and modifications.

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Contents

1. Introduction

Agricultural soils can act as sources or sinks of three greenhouse gases: nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4). Fluxes of these gases are based on biological processes and therefore depend on factors that can have complex interactions

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and exhibit high degrees of temporal and spatial variability (Smith et al., 2008a; Giltrap et al., 2010). Agriculture releases substantial amounts of CO_2, CH_4 and N_2O into the atmosphere (Cole et al., 1997; IPCC, 2001; Paustian et al., 2004). Carbon dioxide is primarily released through microbial decay or by the burning of plant litter and soil organic matter (Janzen, 2004; Smith, 2004); methane is produced when organic materials decompose in oxygen-deprived conditions, for example, during fermentative digestion by ruminant livestock or in stored manures and rice grown under flooded conditions (Mosier et al., 1998); and nitrous oxide is generated by the microbial transformation of nitrogen in soils and manures. N_2O production is often enhanced when available N exceeds crop requirements, especially in wet conditions (Smith and Conen, 2004; Oenema et al., 2005). Agricultural greenhouse gas (GHG) fluxes are complex and heterogeneous, but the active management of agricultural systems offers possibilities for mitigation.

As GHG emissions are highly sensitive to many factors, including soil type, climate conditions and management practices, high degree of uncertainty is associated with GHG emissions. Direct measurement of greenhouse gas emissions for inventory purposes is impractical as it would require a prohibitively large number of measurements over large areas for long periods of time. Thus, the development of a more process-based approach is desirable. To date, process-based models have been used to estimate agricultural GHG-mitigation potential by comparing alternative agricultural management scenarios at local and national scales (Williams et al., 1992; Lokupitiya and Paustian, 2006; Desjardins et al., 2010; Shepherd et al., 2011; Cui et al., 2014).

DNDC (DeNitrification-DeComposition) is a process-based model of carbon and nitrogen biogeochemistry in agro-ecosystems that was originally developed to simulate N_2O emissions from cropped soils in the United States (Li et al., 1992a). From the time of its initial development, classical laws of physics, chemistry and biology, as well as empirical equations generated from laboratory studies, have been incorporated in this model to parameterize each specific geochemical or biochemical process, and numerous changes have been made to the DNDC model to develop country- or need-specific models (Li et al., 1992b; Frolking et al., 1999; Salas et al., 2005; Li, 2007; Giltrap et al., 2010). The DNDC model can now be used to simulate crop growth, soil temperature and moisture regimes, soil carbon dynamics, nitrogen leaching, and the emissions of greenhouse and trace gases and has been widely used internationally (Li et al., 2003, 2005b; Babu et al., 2005; Tang et al., 2006; Wang et al., 2008).

Fig. 1 Within agro-ecosystems, plant growth plays a crucial role in regulating soil C and N and water regimes and can therefore influence the biochemical or geochemical processes (see Fig. 1). Plant growth is also a crucial component of any ecosystem model as plants remove water, N and other nutrients from soils and consequently can alter a series of biogeochemical reactions. Plants additionally produce biomass, including yield and litter, which provide food security and improve soil resources. Nevertheless, developed crop sub-models are not included in most existing ecosystem models, and most models developed by agronomists are highly parameterized, which is useful for field-scale yield studies but not widely applicable at a regional scale (Grant et al., 1993; Grant, 1995; Parton et al., 1998; Liu et al., 2000; Li, 2002 Grant, 1995; Parton et al., 1998; Liu et al., 2000; Li, 2002). To address this gap, a plant growth sub-model was built in DNDC to simulate the effects of cumulative temperature, N uptake, and water stress on crop growth at a daily time step (Li et al., 1994). The basic rules in this sub-model of the original DNDC model were not newly invented but rather adopted from existing plant growth models. This sub-model forms a bridge between plant growth and C and N biogeochemical cycles.

Currently, improvements to the DNDC plant growth sub-model are neither well documented nor widely understood either by the research community or potential users. To rectify this and to integrate existing data with prior knowledge, this review summarizes the state of the DNDC plant growth sub-model. In particular, this review (1) explores and describes the main developments of different DNDC versions and their plant growth sub-models, (2) reviews the huge variety of alternative approaches, (3) assesses model application in a variety of crop types and (4) highlights the strengths, weaknesses and potential future improvements of the model. Additionally, this review provides a theoretical basis for a comprehensive evaluation of the eco-environmental effects of various crops using a DNDC-based model.

2. Plant growth sub-model evolution

In the early stages of model development, DNDC versions did not contain a plant growth sub-model (Li et al., 1992a). Until 1994,

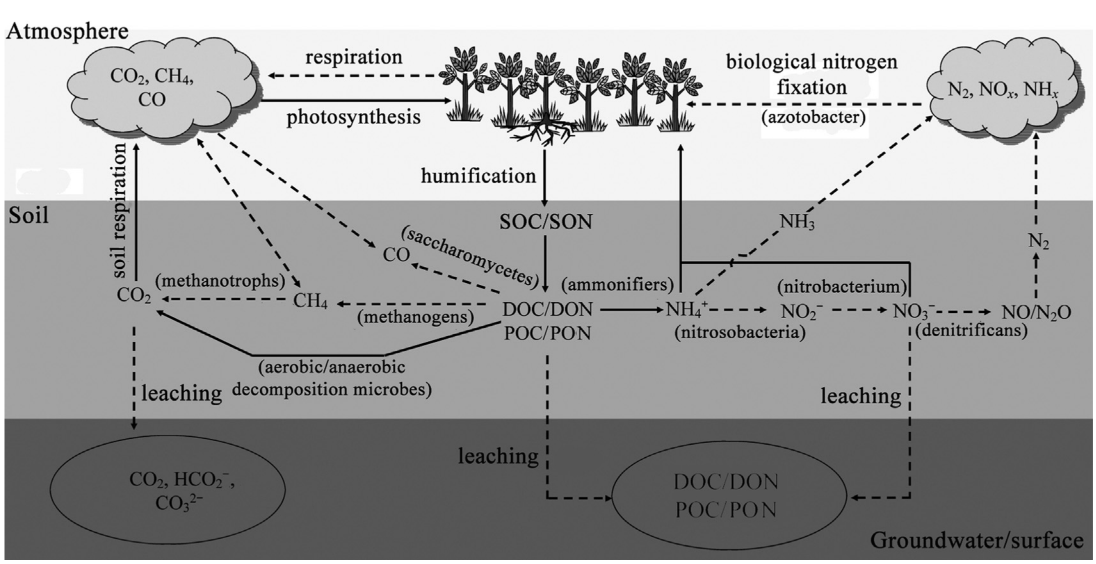

Fig. 1. Generation and consumption of nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) in forest/arable soils and the relationships among these three fluxes (modified from Fang et al., 2014).

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