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Comparison of the DNDC, LandscapeDNDC and IAP-N-GAS models for simulating nitrous oxide and nitric oxide emissions from the winter wheat–summer maize rotation system

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ABSTRACT

The DNDC, LandscapeDNDC and IAP-N-GAS models have been designed to simulate the carbon and nitrogen processes of terrestrial ecosystems. Until now, a comparison of these models using simultaneous observations has not been reported, although such a comparison is essential for further model development and application. This study aimed to evaluate the performance of the models, delineate the strengths and limitations of each model for simulating soil nitrous oxide (N_2O) and nitric oxide (NO) emissions, and explore short-comings of these models that may require reconsideration. We conducted comparisons among the models using simultaneous observations of both gases and relevant variables from the winter wheat–summer maize rotation system at three field sites with calcareous soils. Simulations of N_2O and NO emissions by the three models agreed well with annual observations, but not with daily observations. All models failed to correctly simulate soil moisture, which could explain some of the incorrect daily fluxes of N_2O and NO, especially for intensive fluxes during the growing season. Multi-model ensembles are promising approaches to better simulate daily gas emissions. IAP-N-GAS underestimated the priming effect of straw incorporation on N_2O and NO emissions, but better results were obtained with DNDC95 and LandscapeDNDC. LandscapeDNDC and IAP-N-GAS need to improve the simulation of irrigation water allocation and residue decomposition processes, respectively, and together to distinguish different irrigation methods as DNDC95 does. All three models overestimated the emissions of the nitrogenous gases for high nitrogen fertilizer (>430 kg N ha^{-1} yr^{-1}) addition treatments, and therefore, future research should focus more on the simulation of the limitation of soil dissolvable organic carbon on denitrification in calcareous soils.

1. Introduction

Soils are considered to be sinks or sources of air pollutants such as nitric oxide (NO) and ammonia (NH_3); aquatic pollutants such as nitrate (NO_3^-); and greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These gases are produced mainly by biotic processes regulated by soil environmental factors, for example, temperature, moisture, oxygen availability and substrate supply (Davidson et al., 2012). The high spatial and temporal variabilities of microbial processes require continuous, inter-annual and spatially extensive studies for the regional or global assessment of the biosphere–atmosphere–hydrosphere exchange of carbonaceous and nitrogenous gaseous compounds. However, such studies are generally difficult or even impractical to carry out using only measurements (Frolking et al., 1998; Giltrap et al., 2010). Process-oriented biogeochemical models are highly desirable to improve the limitations of field measurements on a temporal and spatial scale and serve as important tools for predicting and accounting for the release of GHGs and nitrogenous pollutants at all scales.

A variety of process-oriented biogeochemical models have been developed, such as DNDC (Li, 1992a,b, 2007), DAYCENT (Del Grosso et al., 2005), LandscapeDNDC (Haas et al., 2012; Kraus et al., 2014) and IAP-N-GAS (Zhou et al., 2010). Different models in the DNDC family have been extensively used to simulate the release of GHGs and nitrogenous pollutants from croplands (e.g., Beheydt et al., 2007; Cui et al., 2014; Li et al., 2006), grasslands (e.g., Frolking et al., 1998; Saggar et al., 2007)

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and other terrestrial ecosystems (e.g., Lamers et al., 2007; Miehle et al., 2006; Stange et al., 2000). LandscapeDNDC (hereinafter referred to as LDNDC) is a new ecosystem model that generalizes the biogeochemical processes of the cropland and grassland DNDC version (Li, 1992a,b, 2007) and Forest-DNDC (Kesik et al., 2005; Kiese et al., 2011; Li et al., 2000; Miehle et al., 2006; Stange et al., 2000). LDNDC has been used to simulate soil GHGs emissions from croplands, grasslands and forests at local and regional scales (e.g., Chirinda et al., 2011; de Bruijn et al., 2009; Grote et al., 2009b; Haas et al., 2012; Kraus et al., 2014; Miehle et al., 2010). IAP-N-GAS is a simpler model for simulating N_2O emissions from croplands, which performed robustly in East China (Zhou et al., 2010).

According an observation-oriented model development approach (Zhou et al., 2010), model validation is indispensable prior to its use. Validation should be performed with field observation data to assess simulation accuracy and guide further model development (Dietiker et al., 2010). Comparisons between simulation results and observations can aid to assess a model's capacity to represent biogeochemical processes and demonstrate the model's flexibility for predicting ecosystem functions under various conditions (Giltrap et al., 2010). Unsatisfactory validation might reveal model limitations and suggest requirements for model improvement. Because models are constructed based on different philosophies and assumptions (Frolking et al., 1998), each has its own characteristic strengths and limitations. Comprehensive comparisons among different models at the field level are beneficial for understanding discrepancies in modeling schemes and simulation results (Chirinda et al., 2011; Frolking et al., 1998; Li et al., 2005). Based on comparing simulations against observations among several models, many studies (e.g., Chirinda et al., 2011; Frolking et al., 1998; Li et al., 2005) delineated the limitations of individual models and provided suggestions for further development (Chen et al., 2008). More comprehensive comparisons of process-oriented models can help to develop diverse simulation tools (i.e., model ensemble simulations) and improve the reliability of simulations by synthesizing the assessment of different model results (e.g., Frolking et al., 1998).

In this study, the DNDC95 (http://www.DNDC.sr.unh.edu/) with minor changes by Cui et al. (2014), LDNDC (Haas et al., 2012) and IAP-N-GAS (Zhou et al., 2010) models were applied at three field sites in China that had calcareous soils to simulate the N_2O and NO fluxes and other relevant variables, such as soil environmental conditions and yields. Except for the general applicability of the models, the availability of the source code from the modelers is also a key reason that the three models were chosen for comparison. A winter wheat–summer maize rotation with two crops harvested each year has been adopted at these sites. This cropping system predominates in upland agricultural regions in northern China and provides more than half of the food supply (Cui et al., 2012). Integrated observations of gas fluxes and other driving variables at these sites were suitable for comprehensive model validation and a comparison of the model results. Our study aimed to: a) evaluate the performance and applicability of each model for simulating emissions of nitrogenous trace gases and the factors that regulate them in this widely adopted cropping system; b) delineate the strengths and limitations of the models for simulating soil N_2O and NO emissions and c) explore requirements for further development of the individual models.

2. Materials and methods

2.1. Model descriptions

Detailed descriptions of DNDC95, LDNDC and IAP-N-GAS were provided in Li (2007) and Cui et al. (2014), Haas et al. (2012) and Zhou et al. (2010). The following subsections briefly summarize their main features and differences.

2.1.1. DNDC95

DNDC95, with minor changes by Cui et al. (2014), was used in our comparison study. The model consists of two components with six modules in total. The first component, which contains the soil climate, crop growth and decomposition modules, simulates environmental variables, such as soil temperature, moisture, redox potential, pH and substrate concentrations, including soil dissolvable organic carbon (DOC), ammonium and nitrate. The variables are used by the second component, which contains the nitrification, denitrification and fermentation modules that simulate biogeochemical production, consumption and emissions of CH_4, N_2O, NO, and NH_3 and net ecosystem exchanges of CO_2 (NEE), as well as carbon and nitrogen losses from leaching. Input data for DNDC95 include meteorological variables (daily precipitation, daily maximum and minimum air temperatures), soil properties of the cultivated horizon (bulk density, clay fraction, soil organic matter and pH), crop parameters (yield potential, fractions and the carbon to nitrogen ratios of grain, root and straw), management practices including sowing and harvest (dates and fraction of incorporated straw), tillage (dates and depth), irrigation (methods, dates and water amounts), fertilization (types, methods, dates, nitrogen amounts and carbon to nitrogen ratios of organic manure), and other variables (ammonium and nitrate concentrations in rainfall).

DNDC95 simulates the biogeochemical processes in a 0–50 cm soil profile with multiple layers (Giltrap et al., 2010). The depth of each layer is determined by the saturated hydraulic conductivity. Soil physical properties are assumed to be uniform across the soil profile and constant with time, whereas the variables of carbon and nitrogen pools of various layers are initialized logarithmically using the input data. Soil chemical properties, such as the soil carbon content, total nitrogen and pH, also vary due to the occurrence of biogeochemical processes. The soil temperature of each layer is predicted by solving the energy conservation equation across the soil profile. A cascade or bucket modeling approach is adopted to simulate downward soil water movement depending on the water storage capacity (e.g., field capacity) of each layer (Kröbel et al., 2010). If an irrigation event occurs, the amended water is allocated depending on the irrigation method. For flooding, sprinkling and drip irrigation, the water is added to the soil surface and allocated to the topmost layer at 4 mm h^{-1} and injected into 5 cm depth, respectively. Crop growth is estimated as a function of cumulative temperature scaled to optimum crop biomass and regulated by the availability of nitrogen, water and temperature stress. Microbes in the model include nitrifiers and denitrifiers, whose population dynamics are determined by the microbial processes of nitrification and denitrification, respectively. The "anaerobic balloon" concept is applied to determine conditions and allocate substrates for nitrification and denitrification. The processes of nitrification and denitrification occur simultaneously in aerobic and anaerobic microsites, respectively. The sizes of the aerobic (nitrification) and anaerobic (denitrification) fractions are controlled by the soil redox potential using the Nernst equation. The production of nitrogen trace gases during nitrification is defined by the fraction of nitrified ammonium, following the "hole in the pipe" concept (Del Grosso et al., 2000). The fraction values vary with soil moisture, temperature and pH. The reduction of individual nitrogen species involved in the reaction chain of denitrification is simulated with Michaelis–Menten kinetics and the Pirt functions (details are found in the Supplementary materials for online publication (SM): Table S1).

2.1.2. LandscapeDNDC

LDNDC is designed to utilize exchangeable modules to describe ecosystem processes, which have been derived from DNDC and other models. The model has generalized the ecosystem-specific biogeochemistry process descriptions of the DNDC models (arable DNDC and Forest-DNDC) into a universal soil biogeochemistry module for different terrestrial ecosystems. Apart from the biogeochemistry module, the model directly inherits modules for the soil microclimate, water cycle