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Prediction of N_2O emissions under different field management practices and climate conditions

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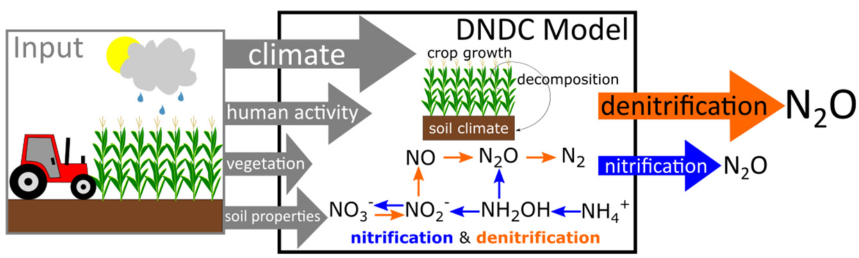
HIGHLIGHTS

- DNDC was evaluated for agricultural N_2O under different management and climates.
- DNDC correctly identified field management that significantly influenced N_2O fluxes.
- DNDC did not predict daily and cumulative N_2O fluxes well, even after calibration.
- N_2O fluxes and model error correlated with precipitation frequency and intensity.
- Model improvements should focus on denitrification surrounding precipitation events.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to the contributions of nitrous oxide (N_2O) to global climate change and stratospheric ozone destruction, it is important to understand how climate and agricultural management affect N_2O emissions. Although the process-based Denitrification Decomposition (DNDC) model is often used for quantifying emissions of N_2O, the accuracy of these predictions remains in question, and it is not clear which input variables, environmental or field management, have the greatest effect on model performance. In this study, DNDC was evaluated for prediction of N_2O fluxes from two climatically-different corn-field sites in the United States (a Colorado irrigated field and a Minnesota rainfed field). Besides climate, these sites offer the additional advantage that measurements are available for multiple field management practices, including fertilizer application, tillage, and crop rotation. This evaluation found that DNDC did not consistently, correctly predict daily-scale N_2O fluxes. Cumulative growing season N_2O fluxes were significantly under-predicted in Colorado and were both under- and over-predicted in Minnesota. Model calibration of four soil input parameters did not significantly improve N_2O emission predictions at either site or time scale. Modeled and measured N_2O fluxes and model error were all strongly correlated with precipitation. Over-predictions of N_2O fluxes were associated with heavy precipitation and high modeled denitrification. Based on our results, model improvements to decrease model error for corn cropping systems in temperate climate zones should focus on better accounting for the effects of precipitation on denitrification. Despite discrepancies in daily and cumulative growing season N_2O fluxes, DNDC correctly identified the only field management (fertilizer application rate) that significantly influenced the measured N_2O fluxes.

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1. Introduction

In the United States, agriculture accounts for 78.9% of nitrous oxide (N_2O) emissions, which contribute to global climate change and ozone depletion (Galloway et al., 2003; USEPA, 2016). Predictive models can help identify locations and times of intense N_2O emissions, compare potential mitigating strategies, and evaluate impacts. Currently, emission estimates are typically based on Tier 1 and/or Tier 3 approaches from the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006; USEPA, 2016). The Tier 1 approach estimates direct emissions from agriculture by applying an emission factor of 1% to nitrogen inputs to agricultural soil (IPCC, 2006). However, this emission factor was determined based on only a few studies and has large uncertainty (0.3–3%) (IPCC, 2006). Tier 3 employs process-based biogeochemical models such as the Denitrification-Decomposition (DNDC) model (Li et al., 1992; Li, 2000) and the daily CENTURY (DayCent) model (Parton et al., 1996). Both DNDC and DayCent simulate soil climate, crop growth, decomposition, and nitrogen mineralization and transformation. DNDC was chosen for this study because it was developed specifically for agricultural ecosystems and considers more N pathways than DayCent (Brilli et al., 2017).

To evaluate any of these models, model results are typically compared to field measurements. DNDC has been evaluated for N_2O emissions from different grasslands and cropping systems, including corn, which has one of the highest nitrogen application rates (66–200 kg N ha^{-1}, USDA (2013)). Results relevant to cultivation of corn have been reported for Canada (Uzoma et al., 2015; Abalos et al., 2016; Congreves et al., 2016), China (Li et al., 2010; Cui et al., 2014; Zhang et al., 2015), Belgium (Beheydt et al., 2007), Australia (Chen et al., 2015), and the United States (Deng et al., 2016). Across the various climate zones and field management practices represented in these studies, DNDC's N_2O flux predictions at the daily-scale were typically poor (e.g., Uzoma et al., 2015; Zhang et al., 2015). For annual N_2O emissions, some studies show model calibration can improve quantitative metrics (e.g., root mean square error) and provide estimates within range of measurement uncertainty (Zhang et al., 2015; Abalos et al., 2016), while others report both under- and over-estimation compared to field measurements (Beheydt et al., 2007; Uzoma et al., 2015; Congreves et al., 2016). Since the impacts of N_2O emissions are of a global scale due to its long lifetime, accuracy in annual N_2O emissions is sufficient for certain applications of the model (e.g., annual greenhouse gas emission inventories). However, the need to calibrate the model for each site and the major discrepancies at the daily-scale suggest that DNDC does not fully reflect the processes leading to N_2O emissions; thus, there is a need to identify how the model can be improved.

The DNDC model has been used in a few previous studies to investigate the influence of field management and climate on N_2O emissions from corn fields. These studies report high N_2O flux peaks associated with fertilizer application (Li et al., 2010; Cui et al., 2014; Abalos et al., 2016; Deng et al., 2016), but the influence of other management (e.g., tillage) is less clear. The model seems to be highly sensitive to precipitation (Deng et al., 2016), and N_2O flux predictions often peak after irrigation or heavy rainfall (Li et al., 2010; Cui et al., 2014; Abalos et al., 2016). Of these studies, only a few considered multiple field management combinations in the same study (Cui et al., 2014; Deng et al., 2016), and none have included multiple field management practices simultaneously with different climate and soil conditions. The ability of DNDC to accurately predict the effects of different management practices, climates, and soil conditions on N_2O emissions, therefore, has not been rigorously evaluated.

The aims of this study are to (1) evaluate the DNDC model for N_2O emissions from two U.S. corn cropping systems under multiple field management combinations and different climate conditions, (2) assess model performance before and after model calibration, and (3) determine variables that influence N_2O emissions and DNDC model performance. Previously published N_2O measurement data from three-year corn-field studies in Fort Collins, Colorado (Mosier et al., 2006), and Rosemount, Minnesota (Venterea et al., 2011), were used for model evaluation. By simultaneously considering multiple field management practices in different climate zones, this study contributes to identification of model processes that are contributing to model error.

2. Materials and methods

2.1. Field sites and N_2O measurement data

Two field sites with different climate, soil properties, and field management were chosen to assess the ability of DNDC to predict N_2O fluxes in climatically-different corn-fields in the US. Detailed information about the field sites, including soil properties, field management, measurement methods, and N_2O emissions are available in Mosier et al. (2006) and Venterea et al. (2011) for Colorado and Minnesota, respectively. Climate and soil data are summarized in Table 1. Field management considered in this study included combinations of tillage (conventional (CT) and no-till (NT)), fertilizer application rates, and crop rotations (continuous corn (CC) and corn-soybean (CB)). In Colorado, fertilizer was injected 5 cm below the soil surface as urea ammonium nitrate 32% at: 0 kg N ha^{-1} (0 N), 134 kg N ha^{-1} (134 N), and high nitrogen (202 kg N ha^{-1} in 2002 and 224 kg N ha^{-1} in 2003 and 2004, HN). In Minnesota, fertilizer treatments were broadcast applied at: 4.5 kg N ha^{-1} starter fertilizer (control, C) and 146 kg N ha^{-1} conventional urea (CU). A total of eight different Colorado treatment combinations (CT-CC-0N, CT-CC-134N, CT-CC-HN, NT-CC-0N, NT-CC-134N, NT-CC-HN, NT-CB-0N, and NT-CB-HN) and four different corn-soybean Minnesota treatment combinations (CT-CU, CT-C, NT-CU, and NT-C) were considered. The Minnesota site was exclusively rainfed, while the Colorado site was supplemented with additional irrigation to meet crop water demands. Both sites collected three midmorning gas samples 1–3 times per week using static chambers (Mosier et al., 2006; Venterea et al., 2011). Gas samples were analyzed for N_2O using a gas chromatograph equipped with electron capture detector and fluxes were calculated using linear and nonlinear methods (Mosier et al., 2006; Venterea et al., 2011). The Colorado dataset included year-round measurements, while the dataset from Minnesota only encompassed the growing season. Measured daily N_2O fluxes ranged from 0 to 550 μg N m^{-2} h^{-1} in Colorado and 0 to 170 μg N m^{-2} h^{-1} in Minnesota. Considering all three measurement years together, fertilizer application rate was the only management that significantly influenced N_2O fluxes at both sites.

2.2. DNDC modeling

DNDC (version 9.5, downloaded January 2014) model inputs are ecological drivers, including climate parameters, soil physical properties, vegetation, and anthropogenic activity (Li, 2000). These ecological drivers modify the soil climate (soil temperature, moisture, pH, redox

Table 1
Soil properties and climate for Colorado and Minnesota field sites.

	Fort Collins, CO	Rosemount, MN
Soil texture	Clay loam[b]	Silt loam[a]
Bulk density (g cm^{-3})	1.36[b]	1.45[c]
Soil pH	7.7[b]	6.5[c]
Clay fraction	0.31[c]	0.13[c]
SOC (kg C kg $soil^{-1}$)	0.012[b]	0.028[a]
Average temperature (°C)	10.1[d]	6.9[d]
Average high temperature (°C)	17.6[d]	12.3[d]
Average low temperature (°C)	2.7[d]	1.4[d]
Average annual precipitation (cm)	40.8[d]	88.7[d]

[a] Venterea et al. (2011).
[b] Mosier et al. (2006).
[c] Web Soil Survey (USDA, 2017).
[d] US Climate Data (2017).