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# Modeling impacts of fertilization alternatives on nitrous oxide and nitric oxide emissions from conventional vegetable fields in southeastern China

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## HIGHLIGHTS

- We test the DNDC model against $N_2O$ and NO emissions form an intensive vegetable field.
- Reducing N dose to a reasonable level can mitigate N gases emissions while maintain vegetable yields.
- Application of organic manure may significantly stimulate $N_2O$ emission from vegetable field.

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## ABSTRACT

Intensive nitrogen (N) fertilizer application in the vegetable fields of China has commonly occurred during recent decades and may substantially increase both nitrous oxide ($N_2O$) and nitric oxide (NO) emissions. However, the quantification of $N_2O$ and NO emissions from vegetable fields has been rare due to both the lack of long-term field measurements and reliable methods for extrapolating these measurements. Using a unique dataset from a four-year measurement study of an intensively managed conventional vegetable field in southeastern China, we tested a process-based biogeochemical model, denitrification-decomposition (DNDC), for its applicability for quantifying the impact of fertilizer management practices on emissions of N trace gases from vegetable production. The results from the model validation indicate that the simulations of vegetable yields and seasonal cumulative $N_2O$ and NO emissions are consistent with the observations. In addition, DNDC can generally capture the measured temporal pattern of daily $N_2O$ and NO fluxes. The modeled impacts of fertilization alternatives can be summarized as follows: (a) both the type and application rate of N fertilizers play important roles in regulating $N_2O$ and NO emissions as well as vegetable growth; (b) reducing the N application rate to 75% of the conventional amount decreased $N_2O$ and NO emissions by 31% and showed little impact on vegetable biomasses, suggesting that reducing the N dose to a reasonable level would be advisable for both the mitigation of N gases emissions and the maintenance of vegetable production; and (c) replacing synthetic fertilizer under the conventional management practices with organic manure may significantly stimulate $N_2O$ emission by 62% while decreasing vegetable yields. The results from this modeling study may provide useful information for the ongoing debate regarding the optimization of fertilizer use strategies in China. This study also demonstrates the potential of utilizing process-based models, such as DNDC, to quantify and mitigate $N_2O$ and NO emissions from intensive vegetable production through interpreting, integrating, and extrapolating field observations.



## 1. Introduction

To sustain increasing agricultural production, intensive nitrogen (N) fertilizer application is commonly used in modern agriculture. However, the high application rate of N fertilizers with low nitrogen use efficiency (NUE) results in a significant portion of the reactive N moving into the atmosphere, which can lead to

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detrimental consequences (Cassman et al., 2002; Galloway et al., 2003; Vitousek et al., 1997). Both nitrous oxide ($N_2O$) and nitric oxide (NO) are important components of global biogeochemical N cycle and contribute to global warming and deterioration of the atmospheric environment (Galloway et al., 2003; IPCC, 2007; Ravishankara et al., 2009). The atmospheric concentration of $N_2O$ is currently increasing at a rate of 0.2–0.3% $yr^{-1}$ (IPCC, 2007), which is primarily attributed to the use of synthetic fertilizers and organic manure (Davidson, 2009). Although combustion is the dominant source of atmospheric NO, the application of N fertilizers significantly contributes to its emission in agricultural regions. Globally, $N_2O$ and NO released from agricultural soils are approximately 2.8 and 1.6 Tg ($10^{12}$ g) N $yr^{-1}$, respectively (IPCC, 2007).

There is a high demand for the quantification and mitigation of $N_2O$ and NO emissions from N-fertilized croplands (e.g., Bouwman et al., 2002; Smith et al., 1997, 2008). However, the complex mechanisms related to the emission of both gases indicate that the quantification and mitigation will be difficult to perform. In soils, $N_2O$ and NO emissions are subject to complex regulation involving the interaction of numerous environmental factors, such as inorganic N substrates, dissolvable organic carbon (DOC) availability, and oxygen status, among others (Robertson and Groffman, 2007; Williams et al., 1992). The temporal and spatial variability of these controlling factors results in heterogeneity with regard to the production and consumption of N gases in soils (Bouwman et al., 2002). A large number of measurements have been performed worldwide to quantify $N_2O$ and NO emissions and to seek effective mitigation options. However, the measurement approaches are usually limited by their spatial or temporal coverage. To extrapolate the results that are measured at specific sites and during specific time periods to large regions or over extended time spans, a variety of modeling approaches, which range from simple regressions to process-based models, have been developed. Simple regression models usually ignore some natural or management factors, which are in fact critical for $N_2O$ or NO production in soils. Due to the disregard for the details of farming management practices, simple empirical models may have missed options that effectively mitigate the emissions of N gases (Giltrap et al., 2010; Li et al., 2005). Therefore, process-based models were developed to fill this gap. Among the process-oriented modeling efforts, the denitrification-decomposition (DNDC) model has been recognized as a useful tool to simulate both carbon (C) and N cycles in agro-ecosystems. DNDC has been evaluated against datasets of $N_2O$ or NO fluxes that were measured worldwide (e.g., Babu et al., 2006; Beheydt et al., 2007; Li, 2000; Giltrap et al., 2010; Wang et al., 2012). However, there are few cases of vegetable fields among the reported studies. The use of DNDC to simulate the C and N cycles in vegetable fields would be a challenge because vegetable fields are more intensively managed with practices that may not apply to other crops.

Since the 1980s, vegetable production has developed rapidly in China due to increasing demand because cultivation of vegetables usually provides more income for farmers. The acreage of vegetable cultivation increased from 0.316 million ha in 1980 to 1.841 million ha in 2009 (http://zzys.agri.gov.cn). Compared to most cereal crops, such as maize, wheat, or rice, the cultivation of vegetables demands a greater amount of N fertilizer. For instance, it is common for Chinese farmers to apply synthetic N-based fertilizers at rates of 200–750 kg N $ha^{-1}$ $season^{-1}$ for vegetables (Zhu et al., 2006); whereas only 250–350 kg N $ha^{-1}$ $season^{-1}$ is used for non-vegetable crops (Ju et al., 2009). In addition, the majority of vegetable fields in China receive organic manure concurrently at a quantity equivalent to at least half the amount of synthetic N applied (e.g., Huang et al., 2006; Mei et al., 2009; Zhu et al., 2006). As a result, N fertilizers are usually applied at much higher rates than recommended (Zhu et al., 2006). The fertilizer N use efficiencies of vegetables are only approximately 20%–50% in China (e.g., Huang et al., 2006; Zhu et al., 2006), and intensive N application has increased the vegetable yields but has also significantly stimulated $N_2O$ and NO emissions from vegetable fields (e.g., Deng et al., 2012; Li and Wang, 2007; Mei et al., 2009, 2011; Pang et al., 2009). Combined with high N inputs and other intensive management practices, including the use of organic manures with low C to N (C/N) ratios, vegetable fields are most likely becoming hot spots for $N_2O$ and NO emissions. Measurements also show large spatial and temporal variability in $N_2O$ or NO emissions from agricultural soils cultivated with vegetables. Based on reports in the literature, the direct emission factors ($EF_d$s), which are defined as the loss rate of applied N via $N_2O$ or NO release in the current season or year, ranged from 0.06% to 14.5% for $N_2O$ and 0.05%–28.2% for NO (Deng et al., 2012; Mei et al., 2009, 2011; Pang et al., 2009). These wide ranges of $EF_d$s suggest that a large uncertainty may occur if using either simple regression models or emission factors with certain constant values to estimate the seasonal or regional $N_2O$ and NO emissions. Therefore, it is necessary to use process-oriented models, which generally take into account additional regulating factors, including natural variables and management practices, to support the quantification or mitigation of N gas emissions.

A field study of $N_2O$ and NO measurements was performed at a conventional vegetable field in southeastern China from 2004 to 2008 (Mei et al., 2009, 2011). The data resulting from this field study provided an opportunity for us to evaluate the applicability of DNDC for modeling $N_2O$ and NO emissions from intensively managed vegetable fields and for investigating the mitigation options of fertilization practices. In this study, we report how we tested the DNDC against the multi-year field measurements and how we then utilized the validated model to assess the impact of alternative fertilization practices on vegetable production and the emissions of both N gases.

## 2. Materials and methods

### 2.1. Description of the field measurement study

The measurement study was performed at a conventional vegetable field located in a suburb (N 32°35′, E119°42′, 4 m above sea level) of Yangzhou city in the Jiangsu province of China, and lasted from September 2004 to October 2008. The field site experiences a sub-tropical monsoon climate with an annual mean precipitation of 1080 mm and an annual mean air temperature of 14.9 °C. The soil is a sandy loam classified as a Shajiang Hapli-Stagnic Anthrosol in the Chinese soil taxonomic classification with pH ($H_2O$) 7.9, bulk density 1.2 g $cm^{-3}$, clay (<0.002 mm) fraction 14%, silt (0.002–0.02 mm) fraction 29%, sand (0.02–2 mm) fraction 57%, soil organic carbon (SOC) content 15.6 g C $kg^{-1}$, total nitrogen 1.58 g N $kg^{-1}$, and total porosity 51% (Mei et al., 2009). The soil has been conventionally cultivated with upland vegetables for approximately 20 years prior to 2004 when the field study began. Prior to vegetable cultivation, the soil was cultivated with rice-wheat or rice-rapeseed rotation systems.

The measurements of $N_2O$ and NO fluxes spanned four years and included 13 vegetable growing seasons and a short fallow period, which are denoted as P1 through P14 in Table 1. All farming management practices at the test site, such as vegetable species, planting and harvest dates, fertilization timing and application rates, tillage, and irrigation, were performed following the conventional management practices of the region and were recorded for validation of DNDC. Additional details regarding the management practices during the entire four-year campaign were described by Mei et al. (2009, 2011) and are summarized in Table 1.