Simulating N_2O emissions from maize-cropped soil and the impact of climatic variations and cropland management in North China Plain

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Abstract
The Water and Nitrogen Management model (WNMM) was applied to simulate N_2O emissions from a semi-arid and maize-cropping system on a loam soil at Yuci in the North China Plain (NCP) from May 2007 to September 2007. WNMM satisfactorily simulated crop growth, soil water content and soil temperatures at depth and N_2O emissions from the soil, compared with the field observations during calibration and validation. About 89% of total N_2O emissions were estimated as nitrification-induced, according to WNMM simulation for this semi-arid and intensively cultivated maize-cropped soil. The calibrated and validated WNMM was then deployed to simulate N_2O emissions from this soil from 1951 to 2007 for nine management scenarios of N fertiliser application at Yuci. This sensitivity test found that the annual N_2O emissions for this system were significantly correlated to annual N fertiliser application rate (r=0.81) and maize yield (r=0.43). Based on this 57-year simulation, multivariate regression models for estimating annual N_2O emissions were developed to account for climatic variation (including annual solar radiation and rainfall) for this semi-arid and intensively cultivated maize-cropping system in the NCP.

Key Words
N_2O Emissions, maize-cropped soil, WNMM simulation, impact of climatic variation.

Introduction
Nitrous oxide (N_2O) is a potent greenhouse gases contributing to global warming and the depletion of ozone in the stratosphere (IPCC2006). Consequently numerous studies have investigated N_2O emissions from agricultural soils cropped with maize (Li *et al*. 2002; Timothy *et al.* 2006; Song *et al*. 2009). Process-based models not only be used to simulate the complex dynamic processes of soil nitrification and denitrification, and their contributions to N_2O production and emissions, but also have powerful advantages to be used to identify main driving factors for N_2O emissions, such as soil properties, crop rotation, management and climate (Gabrielle *et al.* 2006; Grant *et al.* 1993; Li *et al.* 1992; Li *et al.* 2007; Parton *et al.* 2001). The obvious advantages of using such process-based models are: i) to test the proposed theories of N_2O production from nitrification and denitrification processes from agricultural soils, which were mostly developed from laboratory experiments, compared to the field observations, ii) to demonstrate continuous inter-annual variations of N_2O emissions, and iii) to help us to find the knowledge gaps between what has been documented in the books and also been applied in the models and what is really happening in the fields, by comparing model predictions to field observations.

Method
Field experiments were conducted from May 2007 to September 2007 at the Yuci in the NCP (37°38′ N, 112°51′ E, elevation 789 m). A completely randomised design with three replicates was deployed with two fertilization *treatments*: TF = traditional fertilization and OF = optimal fertilization. The study site and experiment treatment information had been detailed by Liu *et al*. (2008).

Methodology
We used one-season (May-September 2007) field observations for N_2O emissions from TF and OF treatments for the model calibration and validation, respectively. Then, the WNMM was used to simulate long term N_2O fluxes using historic weather dataset from 1951 to 2007 (57 years) and simulated various N fertiliser application scenarios to investigate the sensitivity of N_2O emissions to climatic variation (annual air temperature, annual precipitation and annual pan evaporation), N application rate and crop yield.

Results and discussion

Soil water content, soil temperature and N_2O calibration

A tipping-bucket water balance module in WNMM was used to simulate soil water infiltration, redistribution and percolation at layers, and soil evaporation and crop transpiration. WNMM predicted the surface (0-10cm) soil water contents satisfactory without any parameter optimisation for the TF (R^2=0.81, RSE=0.032 cm^3/cm^3, n=130 and p<0.001) (Figure 1). In the calibration (the TF treatment), the observed and predicted soil temperature also demonstrated an impressive agreement at 10cm (R^2=0.82, RSE=1.35°C, n=130 and p<0.001 at 10 cm) (Figure 2).

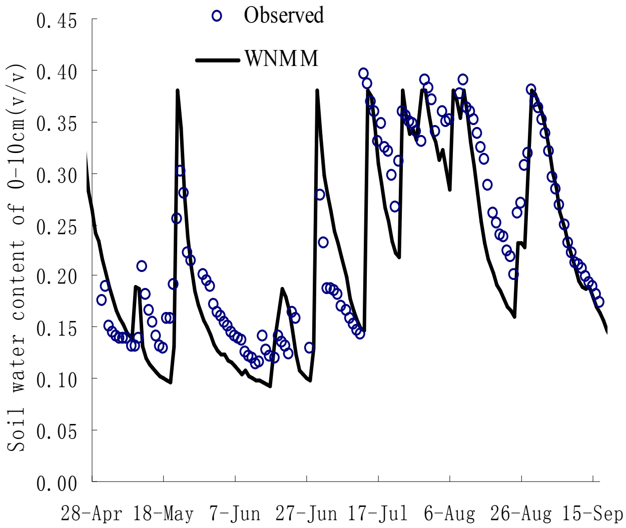

Figure 1. Field observed (hollow circle) and WNMM simulated (solid line) soil water content of 0-10 cm for the Trad treatment at yuci, NPC from May 2007 to September 2007.

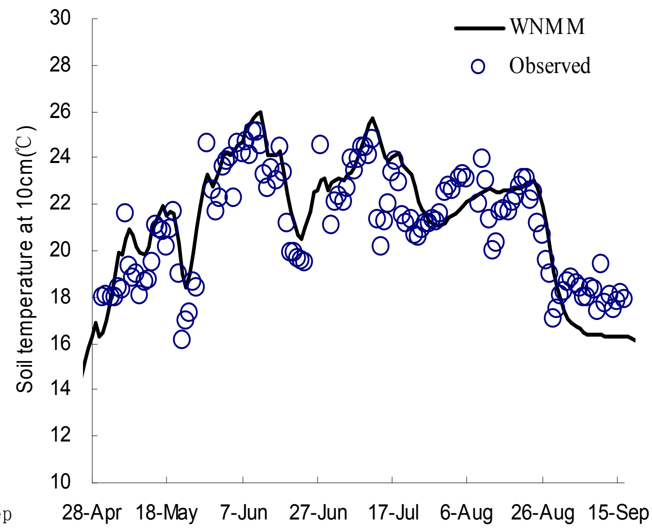

Figure 2. Field observed (hollow circle) and WNMM simulated (solid line) soil temperature at 10 cm for the Tradition treatment at yuci, NPC from May 2007 to September 2007.

The WNMM predicted N_2O emissions for the TF (Figure 3) demonstrated a satisfactory agreement with the chamber observations at the daily basis (R^2=0.80, RSE= 7.28 g N/ha/d, n=130 and p<0.001). The predicted seasonal N_2O emissions for this year is 0.78 kg N/ha/yr, comparable to the chamber observed annual emissions of 1.08 kg N/ha/yr. In addition, nitrification-induced N_2O emissions predicted by the WNMM accounted for 89% of total N_2O emissions.

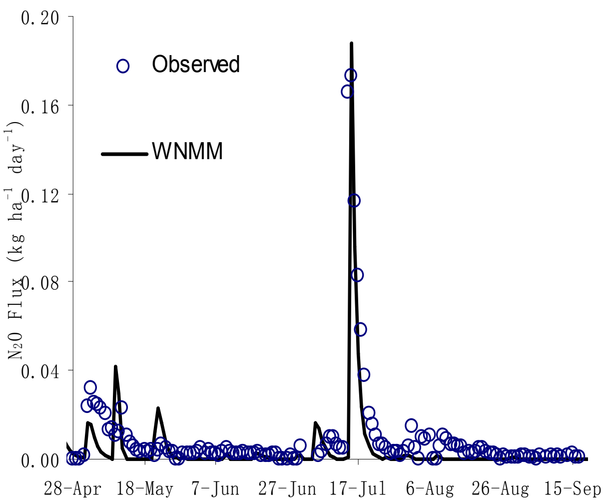

Figure 3. Chamber observed (hollow circle) and WNMM simulated (solid line) N_2O emissions in the TF.

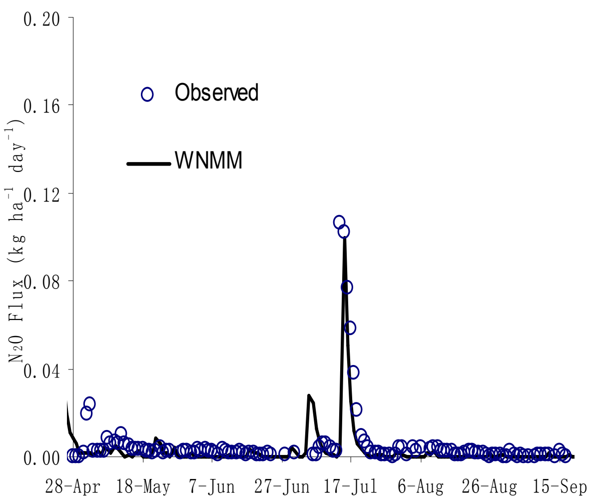

Figure 4. Chamber observed (hollow circle) and WNMM simulated (solid line) N_2O emissions in the OF.

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WNMM model N_2O validation

The validation of daily N_2O fluxes for the OF was satisfactory (R^2=0.49, RSE=7.5 g N/ha/d, n=130 and p<0.001) (Figure4). Based on the WNMM simulation, 0.47 kg N/ha/yr were emitted from May 2007 to September 2007, in which 89% are nitrification-induced, the observed chamber N_2O emissions for the same season were 0.68 kg N/ha/yr in the OF.

Impacts of N application rate and climatic variation on annual N_2O emissions

The 57-year averages of annual N_2O emissions for nine fertiliser N application scenarios indicated a positive correlation between annual N_2O emissions and fertiliser N application rates as shown in Figure5. In addition, N_2O emission factor (EF, 0.25-0.61%) is smaller than 1% recommended by IPCC (2006) and decreases with the increase of the fertiliser N application rate. A Pearson correlation analysis was carried out to look at the statistical relationship between the 57-year WNMM-estimated annual N_2O emissions and related indices, such as climatic variables, fertiliser N application rate and crop yield, Annual N_2O emissions have positive and highly significant correlations with fertiliser N application rate (r=0.81) and maize yield (r=0.43) annual.

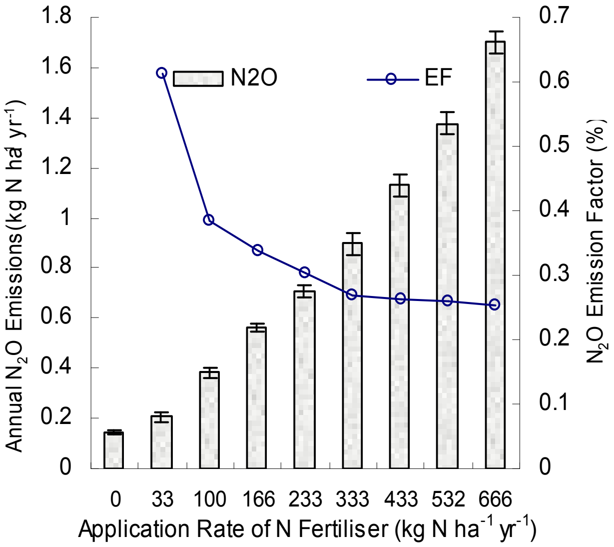

Figure 5. The 57-year averages of WNMM-estimated annual N2O emissions (gray bars) and N_2O emission factor (solid line) (%, not corrected for background emissions) for nine fertiliser N application scenarios at yuci, NPC. The bars represent ±standard deviations of annual N_2O emissions.

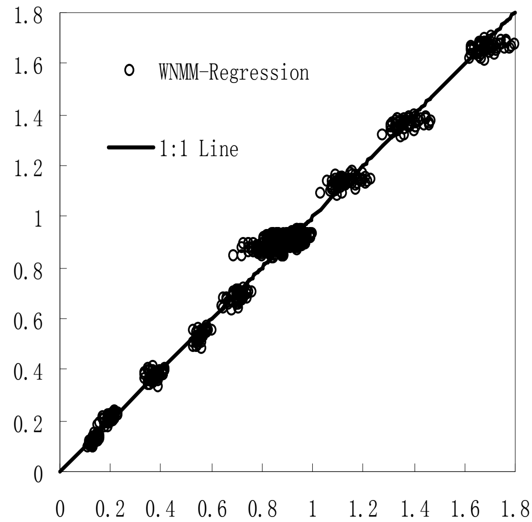

Figure 6. Annual N_2O emissions predicted by the multivariate regression (N rate, rainfall, minimum/maximum temperature, solar radiation, and yield are predictors) (N = 1207, p<0.001, R^2=0.99, S = 0.04105). The multivariate regression indicates that the fertilization and yield are the most important factors driving N_2O emissions.

In this semi-arid agroecosystem, maize yield is mainly controlled by annual precipitation (r=0.52) and fertiliser N application rate (r=0.38) based on WNMM simulations in this study. It is generally expected that higher rainfall results in more denitrification, therefore, potentially contributing to more N_2O emissions from the soil. On the other hand, the increase in rainfall may increase crop growth resulting in more N uptake and possibly more nitrate leaching, consequently reducing the nitrate availability in the topsoil for soil denitrification process. Furthermore, 89% nitrification-induced N_2O fraction estimated by WNMM also indicated that annual N_2O emissions from this agroecosystem are mainly controlled by N inputs (organic N mineralisation and fertiliser N application) and abiotic factors (soil water content and temperature), which strongly impact soil nitrification process and crop growth as well. Thus, crop growth may be another important factor to effect annual N_2O emissions from this soil.

Including climatic variables (annual average minimum air temperature, annual precipitation and annual pan evaporation) and the fertiliser N application rate and maize yield as predictor variables, multivariate regression models were developed for estimating annual N_2O emissions by the stepwise multiple linear regression process:

$$Y=0.1579+0.0023X1+0.0107X2-0.0153X3+0.0001X4+0.00001X5 \quad (1)$$

where Y is the annual N_2O emissions (kg N/ha/yr), X1 is the annual N fertilizer application rate (kg N/ha/yr), X2 is the difference between annual average maximum temperature and annual average minimum temperature difference (°C)， X3 is the average annual solar radiation, X4 is the annual rainfall (mm), and X5 is the maize yield (kg/ha). In general, Eq. (1) explained over 84% of the yearly variations of annual N_2O emissions predicted by WNMM (n=1207 and p<0.001) (Figure 6).

Conclusions

By comparing with the field observations for the TF, the simulation here indicated that WNMM is capable of simulating soil water and soil temperatures. And, the chambered-observed soil N_2O emissions were well predicted by the WNMM for the OF. The 57-year (1951-2007) backward simulations using the calibrated and validated WNMM under nine scenarios for fertiliser N application indicated that annual N_2O emissions simulated by WNMM were significantly correlated to the N fertiliser application rate and the maize yield. By applying a stepwise multiple regression, multivariate regression models with annual rainfall, fertiliser N application rate and maize yield as predictors were developed to estimate annual N_2O emissions, which explained over 84% of between-year variations in annual N_2O emissions predicted by WNMM.

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