Modelling N_2O emissions from agroecosystems: the WNMM experience

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Abstract
Nitrous oxide (N_2O) is primarily produced by the microbially-mediated nitrification and denitrification processes in soils. It is influenced by a suite of climate and soil variables, interacting soil and plant nitrogen (N) transformations as well as land management practices. Numerous simulation models have been developed to predict N_2O emissions from agroecosystems. In this paper, we report on our experiences of simulating N_2O emissions from irrigated maize-wheat, irrigated wheat, rainfed wheat, irrigated pasture and sugarcane ecosystems by using the Water and Nitrogen Management Model (WNMM).

Key Words
Nitrous oxide, agroecosystems, WNMM; simulations.

Introduction

N_2O is a potent and long-lived greenhouse gas, contributes a Radiative Forcing of +0.16±0.02 W m^{-2} of the atmospheric greenhouse effect, and is very effective in absorbing infrared radiation, and its global warming potential is 310 times greater than carbon dioxide (CO_2) for a 100-year time horizon. Anthropogenic activities contributing to N_2O emissions include the application of N fertilizers, crop biological N fixation, tillage, irrigation, animal manure, aquifers, sewage, industry, automobiles, biomass burning, land clearing and trash incineration. More than 60% of N_2O emissions come from soil-based processes (Prather *et al*. 1995). Globally, agricultural lands contribute about 35% of all N_2O emissions (FAO/IFA 2001). The production of N_2O from soils is primarily from the microbially-mediated nitrification and denitrification processes. N_2O flux from soils, relatively small compared to other N fluxes, is dependent on soil temperature, soil water content, O_2 availability, N substrate availability (nitrate and ammonium), and organic C substrate availability (Davidson 1991). All these regulators are strongly influenced by climate, vegetation, soil properties (bulk density, organic matter, pH and clay content), and land-use management or agricultural practices. N_2O production is also influenced by other complex interacting N processes in the plant-soil N cycle, such as plant N uptake, ammonia volatilisation and nitrate leaching. All these influencing variables and processes contribute to high spatial and temporal variability of N_2O emissions. Computational models, which simulate N_2O emissions from soils by integrating all the influencing variables and interacting processes, provide a useful means of assessing gas fluxes at field-to-regional scales (Chen *et al*. 2008). Since the first Focht's N_2O simulation model, various models were constructed to predict N_2O production from nitrification and denitrification in agroecosystems, such as NGAS (Mosier *et al*. 1983), DNDC (Li *et al*. 1992), NLOSS (Riley and Matson 2000), ecosys (Grant 2001), DAYCENT (Parton *et al*. 2001), WNMM (Li *et al*. 2005), FASSET (Chatskikh *et al*. 2005), CERES-NOE (Gabrielle *et al*. 2006) and so on. The WNMM has been applied to simulate N_2O emissions from the intensively-irrigated maize-wheat system in the North China Plain (NCP), the irrigated wheat system in Mexico, the rainfed wheat, irrigated pasture and sugarcane systems in Australia.

Methods

WNMM

The WNMM (Li *et al.* 2007) is a spatially referenced (coupled with GIS) biophysical model developed to simulate dynamic soil water movement and soil-crop C and N cycling under agricultural management, for the purpose of identifying optimal strategies for managing water and fertilizer N under intensive cropping systems (mainly wheat-maize) and pasture system. It simulates the key processes of water and C and N dynamics in the surface and subsurface of soils, including evapotranspiration, canopy interception, water infiltration and redistribution, groundwater fluctuations, soil temperature, solute transport, crop and pasture growth, C and N cycling in soil-crop/pasture system, and agricultural management practices (crop rotation, irrigation, N fertilizer application, harvest, and tillage). It runs at the daily time step at a range of scales. Data required by WNMM are categorized as GIS layer information (soil type, land cover, and village administrative boundary); database-formatted source data (soil physical and chemical properties, land use types, and agricultural management practices); referenced data (climatic reference data and crop biological data); and control data (starting date, period of simulation, initial land surface and soil conditions). The detailed description of simulating soil water dynamics, solute transport and crop growth in WNMM is referred to Li *et al*. (2007).

The pasture growth component in WNMM is generally based on GrassGro (Moore *et al*. 1997). Three species of pastures, paspalum, ryegrass and white clover, are simulated, and their growths are controlled by temperature, radiation, water stress and nitrogen stress. The optimal N concentration of pastures (N_o, kg N/kg DM) is described by using the equation:

$$N_o = N_{max} \cdot \left(\frac{agDM}{1000}\right)^{-0.32} \quad (1)$$

where N_{max} (kg N/kg DM) is the maximum N concentration in aboveground dry matter (kg DM/ha) of pastures, in this study, set to 0.02, 0.03 and 0.04 for paspalum, ryegrass and white clover, respectively. N_o is used for estimating the daily pasture N uptake demand. The actual pasture N uptake is computed based on the availability of mineral N contents in soil layers by considering the root density distribution in the soil profile. White clover is assumed to fixate N_2 up to the remaining demand after N uptake. There is no animal production model, but during grazing pastures are removed by considering animal heads, grazing duration and intake rate. Of the grazed pastures, 20% is lost to the soil surface as animal trampling. In addition, an N load is applied to the soil surface as dung and urine.

WNMM simulates the transformations of several N species in agricultural soils, including mineralization of fresh crop residue N and soil organic N, formation of soil organic N, N immobilization to microbial biomass, nitrification, ammonia (NH_3) volatilization, denitrification, and CO_2, NO, N_2O and N_2 emissions from the soil surface. It divides soil C into three pools: fresh residue C; microbial biomass C (living and dead), and humus C (active and passive). The flows between the different pools are calculated as first-order processes in terms of C, and the corresponding N flows depend on the C:N ratio of the receiving pools. The C:N ratios of the various pools are assumed to be constant in the simulation. Mineralization or immobilization is determined as the balance between the release of N during organic C decomposition and immobilization during microbial synthesis and humification. All the rate constants of first-order reactions for C and N transformations in the soil are modified by factors of pH, clay content, temperature, and water content in soil layers. Nitrification and denitrification are considered in WNMM as the only two microbially-mediated processes contributing to emissions of nitrogenous gases from soils. The WNMM simulation of N_2O production from these two processes and emissions from the soil was described by Li *et al*. (2005).

Results

Irrigated maize-wheat system

The WNMM was applied to model N_2O emissions from two loam-textured arable soils grown the summer maize and winter wheat in the NCP, China, compared with 1- (1999-2000) and 2- (1998-2000) year round manual chamber observations (Li *et al*. 2005). The WNMM N_2O predictions for these two soils were highly correlated with the observations (R^2=0.45-0.54), with 2.1-3.4 kg N/ha/y of annual N_2O emissions. In addition, the nitrification-induced N_2O emissions estimated by WNMM accounted for 22-63% of annual emissions for the intensively-irrigated maize-wheat system in the NCP.

Irrigated wheat system

Ahrens *et al*. (2009) used WNMM to simulate the irrigated wheat cropping system for 1994-1997 in Yaqui valley in Mexico with special focus on N_2O and NO emissions. The N_2O estimates by WNMM were fairly comparable with the chamber observations at various N forms, application rates, timing and methods.

Rainfed wheat system

Li *et al*. (2008) applied WNMM to simulate N_2O emissions from a rain-fed wheat cropping system on a loam-textured soil for two treatments, conventional cultivation with residue burn (CC+BURN+N) and direct drill with residue retention (DD+RET+N) at Rutherglen in southeastern Australia from January 2004 to March 2005. Both treatments received the same amount of N fertilisers. The WNMM satisfactorily simulated the soil water content, mineral N contents and N_2O emissions from the soil, compared with the field observations in both treatments. The predicted annual N_2O emissions were low, 0.22-0.31 kg N/ha/y, and the site emission factor of 0.33% (no background emission correction) is much lower than the IPCC default value. The nitrification-induced N_2O emissions (simulated) accounted for 45% and 34% of total N_2O emissions for the treatments of CC+BURN+N and DD+RET+N, respectively. Then, the calibrated WNMM was used to simulate N_2O emissions from this soil with historic daily weather data from 1968 to 2004 for seven scenarios of fertiliser N application. The correlation analysis found that the annual N_2O emissions for this rain-fed wheat cropping system were significantly correlated to the annual average of daily maximum air temperature (r=0.51 for CC+BURN+N and 0.56 for DD+RET+N), annual rainfall (r=-0.56 for CC+BURN+N and -0.59 for DD+RET+N) and fertiliser N application rate (r=0.43 for CC+BURN+N and 0.31 for DD+RET+N). Based on the 37-year historic simulations, multivariate regression models for estimating annual N_2O emissions were developed to account for climatic variation, and explained about 50% of variations of annual N_2O emissions estimated by WNMM.

Li *et al*. (2009) also applied WNMM to simulate N_2O emissions from a rain-fed and wheat-cropped system on a sandy duplex soil at Cunderdin, Western Australia, Australia from May 2005 to May 2007. WNMM satisfactorily simulated crop growth, soil water content and mineral N contents of 0-10 cm topsoil, soil temperatures at depths and N_2O emissions from the soil, compared with the field observations in two fertiliser treatments during calibration and validation. The annual N_2O emissions ranged from 0.09-0.18 kg N/ha/y, with an average emission factor of 0.1%. About 70% of total N_2O emissions were estimated as nitrification-induced, according to WNMM simulation for this semi-arid and wheat-cropped system. The uncertainty analysis by using 10000 Monte Carol simulations indicated that most of N_2O emission variations simulated by WNMM from the soil are contributed from variations of these soil properties of the 0-15 cm topsoil: pH, total N, organic matter, initial mineral N, bulk density and water content at field capacity, and of fertiliser N application rate.

Irrigated pasture system

The dairy pasture system is a high input and high output agricultural production system, and is associated with intensive irrigation and N fertilizer applications. In the study of Chen *et al*. (2009), the daily and total chamber-measured N_2O emissions from an intensively-irrigated pastoral clay loam-textured soil for the non-fertilizer (CK), urea and urine treatments at Kyabram in southeastern Australia from 1 Nov 2003 to 30 Jun 2005 (one year and eight months) were compared with the predictions by WNMM. The results suggested that WNMM was capable to estimate daily and annual N_2O emissions from this intensively-irrigated pastoral clay loam-textured soil for the CK, UREA and URINE treatments, but with different levels of success during different seasons and at different temporal scales, based on the simple linear regression, sliding window correlation and summed correlation analysis of the chamber-observed and WNMM-predicted N_2O emissions. The simulations and statistical analysis carried out in the study indicated that the WNMM performance in predicting the daily and monthly N_2O emissions for three treatments is in this order: CK < UREA < URINE. The periodically-summed correlation analysis also showed that WNMM was more reliable to give the prediction of N_2O emissions at the time scale of around 35 days from this intensively-irrigated dairy pasture system. The WNMM-estimated N_2O emission factor for this ecosystem was around 0.5%. The estimated annual N_2O emissions ranged from 1.5-6.8 kg N/ha/y. The proportions of nitrification-induced N_2O emissions in the simulated annual emissions were 12%, 21% and 45% for the CK, UREA and URINE treatments, respectively.

Sugarcane system

An application of WNMM to predicting both the environmental drivers and the N_2O emissions from a N-fertilized alluvial non-calcic brown soil with sugarcane cropping in a tropical region of eastern Australia was examined (Chen *et al*. 2008). The high soil moisture regimes, high soil temperatures and high levels of available C that characterise Australian sugarcane culture are expected to promote high evapotranspiration and intensify the normal processes of N cycling that lead to N_2O production. Relevant predictions by WNMM were compared with field measurements made over 14 months: evapotranspiration by eddy covariance, soil water content and soil temperature by soil moisture probes and soil thermometers and N_2O emissions by 6 automatic chambers. For the first growing season of 290 days, WNMM predicted the total N_2O emissions reasonably well although there were lags between the predicted N_2O emissions and observations after rainfall events. The observed N_2O emissions over the same period showed a pronounced diurnal cycle and totalled 4.7 kg N/ha.

Conclusion

Considering the strong spatial and temporal variability of N_2O emissions from soils, the WNMM was capable to estimate daily and seasonal/annual N_2O emissions from irrigated maize-wheat, irrigated wheat, rainfed wheat, irrigated pasture, and sugarcane ecosystems at the field scale. Upscaling is an essential requirement, not only for more accurate regional and national inventories, but also for development of site-specific mitigation practices with the increased interest in full greenhouse gas accounting and emissions trading in the agricultural sector. Spatially-referenced and process-based models, such as WNMM, may increase in popularity with more testing.

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