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Modeling the impacts of water and fertilizer management on the ecosystem service of rice rotated cropping systems in China

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ABSTRACT

Detailed information on the impacts of water use and nutrient application on agro-ecosystem services including crop yields, greenhouse gas (GHG) emissions and nitrogen (N) loss is the key to guide field managements. In this study, we use the DeNitrification–DeComposition (DNDC) model to simulate the biogeochemical processes for rice rotated cropping systems in China. We set varied scenarios of water use in more than 1600 counties, and derived optimal rates of N application for each county in accordance to water use scenarios. Our results suggest that 0.88 ± 0.33 Tg per year (mean ± standard deviation) of synthetic N could be reduced without reducing rice yields, which accounts for 15.7 ± 5.9% of the N application in China in 2005. Field managements with shallow flooding and optimal N applications could enhance ecosystem services at a national scale, leading to 34.3% reduction of GHG emissions (CH_4, N_2O, and CO_2), 2.8% reduction of overall N loss (NH_3 volatilization, denitrification and N leaching) and 1.7% increase of rice yields, as compared to current management conditions. Among provinces with major rice production, Jiangsu, Yunnan, Guizhou, and Hubei could achieve more than 40% reduction of GHG emissions under appropriate water managements, while Zhejiang, Guangdong, and Fujian could reduce more than 30% N loss with optimal N applications. Our modeling efforts suggest that China is likely to benefit from reforming water and fertilization managements for rice rotated cropping systems in terms of sustainable crop yields, GHG emission mitigation and N loss reduction, and the reformation should be prioritized in the above-mentioned provinces.

1. Introduction

Rice is one of the major commodity crops and feeds more than half of the world's population (Lobell et al., 2011). Being the largest rice producing country in the world, China contributes 27.3% of global rice production on 18.3% of global paddy fields (FAO, 2013). It is estimated that 20% more rice needs to be produced in China in the coming two decades to meet food demands as population increases (Peng et al., 2009). Meanwhile, rice cultivation has resulted in the degradation of a wide range of agro-ecosystem services in China. For example, China emits approximately 7.41 Tg CH_4 per year, one of the primary non-CO_2 greenhouse gases (GHG), to the atmosphere due to rice planting alone (Yan et al., 2009). Increasing rice cultivation activities likely lead to higher methane emissions in China under environmental conditions with rising temperature and increasing atmospheric CO_2 concentrations (Van Groenigen et al., 2013). In addition, because rice needs to grow in flooded conditions, rice planting typically involves considerable water consumption and nitrogen (N) loss to the environment (Vlek and Byrnes, 1986), which has been found to aggravate water degradation and nutrient pollution in China (Deng et al., 2006; Zhao et al., 2012). Given environmental issues associated with rice planting, there is a need to explore possible solutions that mitigate conflicts between increased food demands and degraded agro-ecosystem services for China (Miao et al., 2010).

Suitable managements of irrigation and fertilization have shown to be capable of enhancing ecosystem services of rice rotated cropping systems by increasing agricultural yields and minimizing environmental pollutions (Burney et al., 2010; Mueller

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et al., 2012). For water schemes, switching continuous flooding to one or several drainages in paddy fields could promote rice yields slightly and reduce water use (Linquist et al., 2015). Intermittent irrigation could also reduce total GHG emissions from rice planting because the overall radiative forcing of CH_4 reduction suppresses that of N_2O stimulation (Xiong et al., 2007). For fertilizer management practices, N fertilization have found to strongly influence rice yields and N loss through biotic and abiotic processes such as ammonia volatilization, denitrification and nitrogen leaching (Zhang et al., 1996; Ramankutty and Foley, 1999). To derive optimal rates of N application that associated with maximum grain yields and minimum N loss, approaches have been developed based on (1) soil mineral N tests that identify the differences between predicted and measured soil mineral N (NO_3^--N and NH_4^+-N) supply (Chen et al., 2006), and (2) regional evaluation method that use numerous field experiments to quantify yield efficiency, net income, and environmental impacts (Zhu and Chen, 2002). Moreover, as found in field experiments and literature reviews, yield-scaled GHG emissions (i.e., GHG emissions per unit rice yield) tend to have minimized values at the rates of N application that optimize rice yields (Feng et al., 2013). Water managements may influence nitrogen use efficiency through various N pathways like denitrification, leaching and ammonia volatilization thus the identification of optimal N rates to achieve the best yield (Sun et al., 2012; Liu et al., 2013). These efforts clearly indicate that strategies of water and N uses hold promise to improve grain yields while reducing GHG emissions and N loss from rice fields, and the water and N managements should be considered simultaneously.

Quantitative evaluations of managements on agro-ecosystem services of rice rotated cropping systems are critical to understand potential environmental benefits from managements, but evaluations over large areas like mainland China are challenging for some reasons. First, conflicting conclusions might be drawn from previous studies when performing meta-analysis, largely owing to incomplete records of field management schemes. For example, the response of CH_4 emissions to N inputs varies with water regimes, while activities like drainage frequency and strength are not well documented among sites (Pittelkow et al., 2014). Second, it can be challenging to capture optimal N rates based on in-situ experiments (Cassman et al., 1998). Third, scaling up from individual sites to large geographical regions is difficult due to spatial variation of climate environment, soil conditions, and management practices (Smith et al., 2010). Thus, regional mitigation potential of GHG emissions and N loss with yield constraints through optimal managements remains highly uncertain. Lastly, physiological models that describe underlying mechanisms of biogeochemical cycles in paddy fields hold great promise to address the issues associated with the meta-analysis method or field measurements. However, due to incomplete modeling strategies and limited data access in China, most of modeling studies have not evaluated the integrated impacts of water and N fertilizer managements on rice rotated cropping systems (Li et al., 2005; Cheng et al., 2013).

Compounding these concerns, the objectives of this study are to (1) quantify national GHG emissions, rice yields, and N loss to the environment from rice rotated cropping systems under varied management scenarios of water and N uses; and (2) identify optimal management combinations that potentially enhance ecosystem services of rice rotated cropping systems in China. To meet these objectives, we applied a biogeochemical model of DeNitrification–DeComposition (DNDC) with county-scale agricultural database that contains climate, soil, vegetation, and management information in China.

2. Materials and methods

2.1. Model descriptions

DNDC is a process-based biogeochemical model that simulates carbon dynamics and trace gas emissions for agro-ecosystems (Li et al., 1992). The DNDC model consists of three primary components that model crop growth, soil environment, and soil microbe processes. The crop growth sub-model tracks phenological development, biomass accumulation and allocation, demand and uptake of water and N, respiration and litter production. The soil environment sub-model simulates soil temperature, soil moisture, soil redox potential (i.e., Eh), soil physical properties, and soil oxygen status. The sub-model of soil microbe processes simulates soil biogeochemistry reactions such as decomposition, nitrification, denitrification and fermentation, in which processes trace gases (such as N_2O, CH_4, NO, and NH_3) are produced. Agricultural management practices, including fertilization, tillage, irrigation, manure amendment and grazing, are considered in DNDC to account for various biogeochemical processes. Though DNDC has considered the impacts of farmland water conservancy facilities together with N contents in flooded water and calculated overflow on N runoff, detailed descriptions of these parameters are challenging to achieve over large regions thus set to constant inside DNDC, which would produce uncertainties in specific regions. Therefore, modeling results of N runoff were not included in this study. DNDC has been widely used to simulate greenhouse gas emission, crop growth, ecosystem carbon dynamics, soil water balance, and vegetation biochemical cycles (Fumoto et al., 2008; Deng et al., 2011; Uzoma et al., 2015).

2.2. Model revision to account for rice transplant

Different from other places in the world, rice cultivation in China often involves practices of transplantation. Rice seedlings are typically transplanted from a seedling bed to paddy fields right after the harvests of previous crops. Transplantation saves growing periods to meet requirements of temperature accumulation, thus it is important for double- and triple-cropping systems in China. Current version of DNDC does not include a function of rice transplantation, such that direct modeling of rice growth and yields tends to be biased for rotated cropping systems. Here, we implement a new scheme and modify DNDC to include parameters that define dates of rice transplantation. The schematic descriptions of crop growth sub-models are shown in Fig. S.1 (see supporting information Appendix A) for comparisons between current and revised versions of DNDC.

2.3. National database construction

To run the DNDC model for more than 1600 counties with rice cultivation in China, we constructed county-level databases that contain soil, weather and management data, including: (1) daily meteorological data with 2-m air temperature (°C) and precipitation (mm); (2) soil parameters with soil organic matter content ($\mathrm{kg\,C\,kg^{-1}}$ soil), clay fraction (0–1), pH, and bulk density ($\mathrm{g\,cm^{-3}}$); (3) Crop parameters with maximum grain yield ($\mathrm{kg\,C\,ha^{-1}}$), effective accumulated temperature (°C), crop water demand ($\mathrm{g\,water\,g^{-1}}$ dry matter), and annual rice yield increase index (%); (4) crop system information with rotation types and areas; (5) field management practices that involve sowing/harvest dates, N fertilizer amounts ($\mathrm{kg\,N\,ha^{-1}}$), irrigation ratios within a county (0–1), tillage dates and methods, manure amounts ($\mathrm{kg\,N\,ha^{-1}}$), crop straw return proportions (0–1), flooding methods, and transplant dates (if rice rotated cropping system). Soil parameters