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Maintaining rice production while mitigating methane and nitrous oxide emissions from paddy fields in China: Evaluating tradeoffs by using coupled agricultural systems models

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A B S T R A C T

China is the largest rice producing and consuming country in the world, accounting for more than 25% of global production and consumption. Rice cultivation is also one of the main sources of anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions. The challenge of maintaining food security while reducing greenhouse gas emissions is an important tradeoff issue for both scientists and policy makers. A systematical evaluation of tradeoffs requires attention across spatial scales and over time in order to characterize the complex interactions across agricultural systems components. We couple three well-known models that capture different key agricultural processes in order to improve the tradeoff analysis. These models are the DNDC biogeochemical model of soil denitrification-decomposition processes, the DSSAT crop growth and development model for decision support and agro-technology analysis, and the regional AEZ crop productivity assessment tool based on agro-ecological analysis. The calibration of eco-physiological parameters and model evaluation used the phenology and management records of 1981–2010 at nine agro-meteorological stations spanning the major rice producing regions of China. The eco-physiological parameters were calibrated with the GLUE optimization algorithms of DSSAT and then converted to the counterparts in DNDC. The upscaling of DNDC was carried out within each cropping zone as classified by AEZ. The emissions of CH_4 and N_2O associated with rice production under different management scenarios were simulated with the DNDC at each site and also each 10 × 10 km grid-cell across each cropping zone. Our results indicate that it is feasible to maintain rice yields while reducing CH_4 and N_2O emissions through careful management changes. Our simulations indicated that a reduction of fertilizer applications by 5–35% and the introduction of midseason drainage across the nine study sites resulted in reduced CH_4 emission by 17–40% and N_2O emission by 12–60%, without negative consequences on rice yield.

1. Introduction

Climate change characterized by global warming has already had observable impact on the ecological system and human society (Alley et al., 2003). The historical records show that from 1901 to 2012, the global mean surface temperature increased by 0.89 °C. This warming trend is expected to continue in the forthcoming decades and would impose even more significant impact on ecosystem and human society (IPCC, 2013). The main cause of current global warming is the anthropogenic emission of greenhouse gases (GHGs), which has led to their increased concentration in the atmosphere. Modern intensive farming, which heavily depends on chemical fertilizer application and irrigation, is the single largest source of methane (CH_4) and nitrous oxide (N_2O) emissions (IPCC, 2014; FAO, 2016). Meanwhile, a warmer climate accompanied by modified water regimes exerts impact on farming practices and consequently on crop productivity (Verburg et al., 2000; IPCC, 2014). Since the global warming potential of CH_4 and N_2O is 25 and 298 times higher than CO_2, respectively (IPCC,

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2013), it is well recognized that a focus on reducing CH_4 or N_2O emissions may be an effective climate change mitigation strategy.

Our ability to pick these "low-hanging fruits" may however be constrained by the existence of multiple, conflicting objectives. Rice paddy cultivation in China represents a significant example to this end. On the one hand, China is the major producer and consumer of rice in the world and maintaining self-sufficiency in rice is extremely important for the country (FAOSTAT, 2016). On the other, China's rice production generates significant environmental pressure, as it depends on large-scale basin irrigation and large amounts of fertilizers applications (Miao et al., 2011). Such practices have resulted in significant emissions of CH_4 and N_2O to the atmosphere, as well as damages to soil and water systems. Using IPCC guidelines for GHG inventories (IPCC, 2006), the emissions of CH_4 from Chinese paddy fields were estimated at 7.41 Tg (1 Tg = 10^{12} g) CH_4-C in 2000, which is well over 150 Tg CO_2eq, accounting for about 29% of world total CH_4 emission from rice in that year (Yan et al., 2009). These emissions levels were maintained throughout the last decade (FAOSTAT, 2016). At the same time, N_2O emissions from Chinese paddy fields were estimated at 0.036 Tg N_2O-N in 2007 (Gao et al., 2011), corresponding to roughly 30% of the total N_2O-N emissions from Chinese agriculture (FAOSTAT, 2016).

In the rice cultivation system, rice grain and greenhouse gas are joint products from paddy fields cultivation and there is a complex relationship between rice growing and GHG emissions. For example, CH_4 production is influenced by substrate concentrations, which are influenced by plant root activities. Plant growth dynamics also influences soil mineral N through crop N uptake, therefore indirectly affecting N_2O emission. This complexity has attracted significant research attention and various GHG mitigation measures have been tested using field experiments at paddy sites. For example, Dong et al. (2011) highlighted the tradeoff relationship between CH_4 and N_2O emissions, finding that an increasing application of nitrogen fertilizer will mitigate CH_4 emission with reference to no fertilization, but increase N_2O emissions at the same time. Itoh et al. (2011) found that employing midseason drainage as a water management technique in rice fields reduced the combined climate forcing of CH_4 and N_2O in comparison with basin irrigation. Based on experimental evidence, Johnson-Beebout et al. (2009) concluded that simultaneous minimization of both CH_4 and N_2O emission could not be maintained in rice soils, but that appropriate water and residue management could nonetheless reduce greenhouse gas emissions. Wu et al. (2008) showed that employing conservation tillage methods, especially no-tillage, mitigated GHG emission from rice fields by about 15%. However, it is difficult to extrapolate these field-based results to large regional scales, because of high inherent variability over space and time. Such variability may instead be addressed by agricultural systems models that, while capturing the fundamental soil crop atmosphere dynamics highlighted by field experiments, can be used to further estimate the regional variability of associated emissions as a function of the wide range of soil, water and climatic parameters that exist over large scales (Jones et al., 2016).

The DeNitrification-DeComposition (DNDC) model is one of the most widely accepted biogeochemistry process-based models in the world (Wang and Chen, 2012; Gilhespy et al., 2014). The model has been evaluated against observations worldwide (e.g., Beheydt et al., 2007; Giltrap et al., 2010; Gilhespy et al., 2014). The development of a GIS coupled to high-resolution soil maps in recent versions of this model, allows DNDC to also estimate GHG emissions at regional and national levels, in support of national inventories and including the impacts of rice rotations (e.g., Gilhespy et al., 2014; Zhang et al., 2016; Li et al., 2005; Chen et al., 2016).

With the GIS application, an array of weather and soil data could be employed to support DNDC model-based regional simulations. However, two limitations currently undermine such simulations. First, the phenological and physiological parameters as the key input of DNDC are typically calibrated with the subjective optimization method (McCuen, 2003), meaning that parameter values are manually adjusted based on the modeler's subjective knowledge of the parameter, model, and data (Wang and Chen, 2012). A consequence of this limitation is that the default cultivar parameter values in DNDC characterize only one rice cultivar for all of China, thus failing to represent the richness and regional diversity of cultivars that exists in this country. Second, as highlighted in Zhang et al. (2016), most DNDC studies were conducted at the county level in the case of China or at large spatial simulation units, with a resolution about 0.5° × 0.5° (e.g., Li, 2000; Pathak et al., 2005; Tang et al., 2006; Gao et al., 2014). This coarseness does not allow to properly capture the impacts of soil heterogeneity and the associated management measures within a county or a large spatial unit, resulting in poor spatial performance of the simulation models.

To overcome the above weaknesses of DNDC and to more accurately evaluate the tradeoffs between maintaining the current level of rice production and reducing GHG emissions from farming activities, we coupled three state-of-the-art agricultural systems models in order to capitalize on their individual comparative advantages. They are the biogeochemistry process-focused DNDC model, the crop growing process-focused model – Decision Support System for Agro-technology Transfer (DSSAT) (Jones et al., 2003), and the Agro-Ecological Zone (AEZ) model (Fischer et al., 2012), a widely used regional crop productivity assessment tool. The two crop simulation models (DSSAT and AEZ) are designed to assess the impacts of multiple climate factors on crop growth and grain yield. They are widely employed in climate impact studies (Challinor et al., 2014; Thorp et al., 2008; Seidl et al., 2001). We investigated how such coupling can improve the spatial performance of DNDC for the case of paddy rice production in China. Our parameters calibration and model evaluation used the observed phenology and management records at nine representative agro-meteorological stations, spanning the major rice producing regions of China. We first calibrated eco-physiological (cultivar) parameters for rice growth using the Generalized Likelihood Uncertainty Estimation (GLUE) algorithm provided by DSSAT, which uses Monte Carlo sampling from prior distributions of the coefficients and a Gaussian likelihood function to determine the best cultivar coefficients, based on the observation data. We then followed a procedure as presented in Section 2.4.2 to convert these eco-physiological cultivar parameters into DNDC required parameters. In this way, we enriched the value set of cultivar parameters of the DNDC model, which is essential for meaningfully upscaling, via the assistance of AEZ, the DNDC runs to the rice cropping zones of China. With such coupling between the three models, we evaluated rice yield levels and the corresponding CH_4 and N_2O emissions under different management scenarios, at a resolution of 10 × 10 km, seeking to highlight those water and fertilizer management solutions that could lead to significant reduction of CH_4 and N_2O emissions without causing reductions in rice production.

2. Materials and methods

2.1. The study sites

We selected nine agro-meteorological observation stations based on the following criteria from the original hardcopy records filed in the Data Center of China Meteorological Administration: (1) each station represents a typical cropping system for rice cultivation in China; (2) they differ in terms of geographic and climatologic characteristics; (3) each station has complete records of crop phenology for more than 20 years over the period of 1981–2010; and (4) each station has complete records of crop management for more than 5 years over the period of 1981–2010. These records include the ID, name and location (latitude and longitude) of each station; date of each major phenological stages (sowing, flowering, maturity, etc.); yield and yield components (grain weight, grain number per tiller, tiller number per plant, etc.); date, type and quantity of fertilizer application; and irrigation