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Modeling biomass, nitrogen and water dynamics in rice–wheat rotations

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ABSTRACT

Rice–wheat cropping systems occupy between 24 and 26 Mha in Asia. A main feature of RW rotations is the alternation of aerobic and anaerobic soil conditions. This alternation of flooded and non-flooded soil conditions is conducive to N emissions, especially with the current high N rates in RW systems. To design alternative management systems, better understanding of the processes underlying emissions is required. For that purpose, the RIce WhEat Rotation model (RIWER) was developed, on the basis of existing crop, water and soil organic matter models, describing the relevant soil processes under both anaerobic and aerobic conditions. RIWER is evaluated using data from RW experiments in China. Assessment of model performance, on the basis of graphical comparison and goodness-of-fit parameters, showed that RIWER performs well in simulating total aboveground biomass, N uptake of cops and soil inorganic N content. The RIWER modeling framework needs further testing, but offers a promising operational tool to support the design of sustainable RW systems, combining environmentally-friendly production methods and high yields.

1. Introduction

Rice–wheat cropping systems occupy 24–26 million ha (Mha) in Asia, mainly in the Indo-Gangetic Plains (IGP) in South Asia and the Yangtse River Basin of China (Timsina and Connor, 2001; Ladha et al., 2003). In South Asia including India and Pakistan, rice–wheat systems occupy 13.5 Mha providing the staple food for about 400 million people (Ladha et al., 2003). In China, rice–wheat systems occupy between 9 and 13 Mha (Timsina and Connor, 2001; Ladha et al., 2003; Dawe et al., 2004), accounting for approximately 10% of the arable land and providing the bulk of the cereals required for feeding its population. To safeguard food security for the Asian population that increases annually with 40 million in the next decade (UNPD, 2009), more cereals need to be produced. In the last decades, yield increases have been mainly the result of the introduction of improved varieties, combined with increasing agrochemical inputs (Richter and Roelcke, 2000; Hafner, 2003; Tong et al., 2003). Recent studies suggest that yield growth in both wheat and rice is declining, while their production has been associated with environmental problems such as soil erosion and pollution of surface water with nutrients and biocides (Zhang et al., 1996; Li et al., 2000; Zhu et al., 2000; Cassman et al., 2003; Ladha et al., 2003; Tong et al., 2003; Tian et al., 2007). Crop management in rice–wheat (RW) systems therefore should be modified towards more sustainable systems that combine environmental-friendly production methods and high yields.

A main characteristic of RW rotations is the alternation of aerobic and anaerobic soil conditions (Timsina and Connor, 2001), which strongly affects microbial C and N dynamics (Fierer and Schimel, 2002; Gu et al., 2009) and increases inorganic soil nitrogen during rewetting (Qiu and McComb, 1996; Appel, 1998; Lundquist et al., 1999). Excess mineral N that cannot be taken up by the crop may be lost through denitrification (Reddy et al., 1989; Qiu and McComb, 1996). These complex processes need to be better understood and quantified as a basis for improvements in crop management in RW systems that increase yields as well as nitrogen and water use efficiencies. Modeling is an important and effective tool for explicitly describing the relationships among the components of complex systems. Modeling contributes to increased insight into relevant processes and their interactions, and can be applied to study effects of crop management, and to explore possible consequences of management modifications (Van Keulen, 2001). The challenges for application of existing models to simulate RW systems are the regular alternation between anaerobic and aerobic conditions and associated consequences for decomposition of soil organic matter, nitrification and denitrification (Probert, 2002). The crop growth models CERES-Rice and CERES-Wheat (CERES: Crop Estimation through Resource and Environment Synthesis) have been applied for studying RW systems in northern Bangladesh and northwest India (Timsina et al., 1998;

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Sarkar and Kar, 2006). Both, the rice and the wheat model performed satisfactorily under both water and N non-limiting conditions. However, available evidence suggests that both crop models do not perform well in resource-limited situations, while the soil organic model did not perform well under anaerobic conditions (Timsina and Humphreys, 2006). Especially, understanding of soil organic matter decomposition under anaerobic conditions is limited. Therefore, most of the existing soil organic matter models have been developed for aerobic conditions (Shibu et al., 2006). Simulation of RW rotations requires models that describe the dynamics of soil hydrological conditions associated with growing continuously flooded rice in sequence with wheat grown in non-saturated soil, and their profound impact on nutrient dynamics, especially N (Timsina and Humphreys, 2006).

In this study, a modeling framework for RIice WhEat Rotations (RIWER) is developed, taking into account the specific characteristics of water and nitrogen dynamics in these systems. Our framework is based on two Wageningen models (Bouman et al., 1996; Van Ittersum et al., 2003), ORYZA2000 for rice (Bouman et al., 2001) and SWHEAT for wheat (Van Keulen and Seligman, 1987), and the water model PADAHE that combines two water modules PADDY (Wopereis et al., 1996) and DRSAHE (Van Keulen, 1975; Stroosnijder, 1982) with the soil organic matter model SOM (Jongschaap, 1996), adapted for both aerobic and anaerobic conditions. RIWER is evaluated in this study using field data of RW rotations in China.

2. Model description

2.1. Model structure and operation

RIWER consists of a management module (MAN), two crop modules ORYZA2000 and SWHEAT, a soil module including the water module PADAHE and the soil organic matter module (SOM). The latter two in combination, simulate inorganic soil nitrogen processes (Fig. 1). Each module has its own data file.

RIWER operates within the simulation shell FSE3.0 (FORTRAN Simulation Environment), developed by Van Kraalingen (1995). The FSE-driver checks the model components and continues execution, with a daily time step, until a user-defined end date is reached. During execution the various modules in RIWER run individually, and they mutually interact by exchanging daily values of variables, such as mineralized N, soil water content, daily crop N uptake, transpiration, etc. The crop modules stop execution at harvest time, while the soil module continues execution during the fallow period, until a new crop is sown/planted, initiated by the input data specified in the management module. The simulation cycle of rice and wheat continues until the user-defined end time is reached.

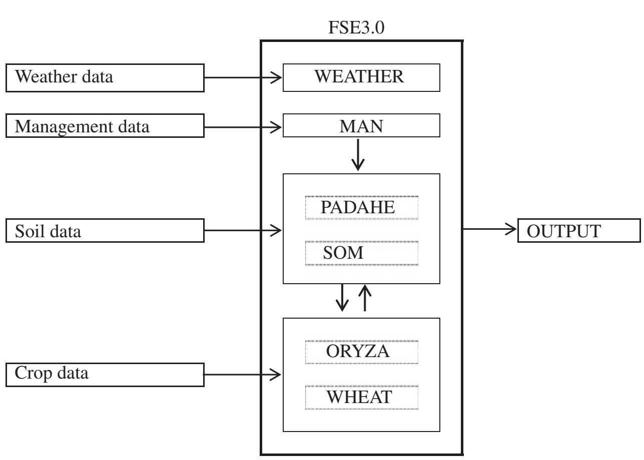

Fig. 1. Structure of the rice wheat rotation model (RIWER). Arrows indicate flows of information (see text for explanation).

2.2. Crop modules

ORYZA2000 is an ecophysiological crop model, described in detail by Bouman et al. (2001). Briefly, ORYZA2000 simulates growth and development of rice for potential, water-limited and nitrogen-limited production situations. It has been evaluated under nitrogen- and/or water-limited conditions in the Philippines (Bouman and Van Laar, 2006), Indonesia (Boling et al., 2007), China (Belder et al., 2007; Feng et al., 2007; Jing et al., 2007, 2008), Japan and Thailand (Jing et al., 2008). In this study, a soil organic matter module (SOM, see following section) is linked to ORYZA2000 to replace the original N module. Actual crop N uptake is the minimum of available soil nitrogen and crop demand. It is assumed that all mineral nitrogen (nitrate and ammonia) in the wet part of the rooted zone is available to the well-rooted crop within a relatively short time, either through mass flow or diffusion (Seligman et al., 1975). Nitrogen uptake by mass flow (N_{mass}) in both rice and wheat is driven by transpiration:

$$N_{mass} = \sum_{i}^{n} W_{massi} \times N_{ci} \quad (1)$$

where W_{massi} is mass flow of water to the roots in the ith soil compartment, N_{ci} is the concentration of mineral N in the ith soil compartment.

When total uptake by mass flow does not meet total demand for nitrogen of the crop, an unfulfilled demand can be met by diffusion when mineral nitrogen is available. The overall equation for uptake by diffusion is:

$$N_{m-d} = \begin{cases} \max(0, N_d - N_{mass})/\tau & DVS < 1.0 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where N_d is the total N crop demand, τ is a time constant for diffusion of soil mineral nitrogen to the roots, DVS is the crop development stage. Diffusion stops when translocation of carbohydrates to the root system ceases, i.e. after anthesis (indicated by $DVS < 1$), because available energy then limits active uptake of nitrogen.

SWHEAT is a similar ecophysiological crop model, developed for aerobically grown wheat crops and simulating dry matter accumulation, phenological development, assimilate distribution, and organ formation (Van Keulen and Seligman, 1987). It accounts for effects of moisture and nitrogen deficiency on growth, organ formation and yield. The model uses an integration time step of 1 day.

Dry matter accumulation starts from calculating potential gross CO_2 assimilation as a function of daily radiation and total green plant area, based on an exogenously defined photosynthesis-light response curve of individual leaves, characterized by its initial light use efficiency and the diffusion limited maximum assimilation rate at high light intensities (Goudriaan and Van Laar, 1978). The effect of temperature on gross assimilation is taken into account through a reduction in the light-saturated assimilation rate when daytime air temperatures are below 10 °C. Leaf nitrogen status also affects the light-saturated assimilation rate. Soil moisture availability is accounted for by assuming a proportional relation between the reduction in transpiration and in gross CO_2 assimilation. Respiration is subdivided into two components: maintenance respiration is calculated as a fraction of plant dry weight, taking into account the effect of temperature and nitrogen content; growth respiration is expressed as the conversion efficiency from assimilates into structural plant material, taking into account the composition of