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Modelling the effect of mulching on soil heat transfer, water movement and crop growth for ground cover rice production system

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ABSTRACT

Soil-crop system models often failed to simulate the effect of plastic film mulching (FM) on soil heat transfer, water movement and crop growth due to lack of appropriate method and the measured data in the fields. The objectives of this study were to (i) improve the Soil Water Heat Carbon Nitrogen Simulator (WHCNS) model to simulate soil temperature, water content and rice growth under FM condition, and (ii) to analyze the effect of FM on water balance and water use efficiency (WUE) under different water and nitrogen (N) management, using the data of a two-year field experiment with a factorial design of two water (W_{sat} and $W_{80\%}$, soil water content was kept at saturation and 80% field capacity) and three N levels (N1: zero-N fertilizer; N2: 150 kg urea N ha^{-1}; and N3: 75 kg urea N ha^{-1} plus 75 kg N ha^{-1} as manure) treatments. The results showed that the modified model accurately simulated the changes in soil temperature, soil water content, LAI, dry matter and yield under FM condition. The normalized root mean square error (*nRMSE*) were 4.7%, 4.5%, 24.5%, 16.5% and 7.9%, respectively, which were significantly smaller than the results simulated by the original model. Importantly, although there were no significant differences in average crop yields between two water input levels ($W_{80\%}$ and W_{sat}), the amounts of irrigation and evaporation under $W_{80\%}$ treatment were reduced significantly by 71.9% and 36.2%, respectively. And the WUE of $W_{80\%}$ (1.13 kg m^{-3}) was higher than that of W_{sat} (0.84 kg m^{-3}). The ranking of WUE under different N management for $W_{80\%}$ treatments was $N2 \approx N3 > N1$. In conclusion, the modified WHCNS model performed significantly better in simulating the dynamics of water, heat, and crop growth under FM. Reduced irrigation with 80% field capacity and applying 75 kg urea N ha^{-1} plus 75 kg N ha^{-1} as manure can achieve "more yield with less water".

1. Introduction

Rice is the primary cereal of tropical and some temperate regions. The global rice production has been increased dramatically, from 285 million ton in 1961 to 745 million ton in 2013, due to improved cultivar, irrigation facilities, fertilization and other field management (FAO, 2016). China is the world's largest rice production country, with a planting area of 30 million hectares which accounts for 18.7% of world's total (FAO, 2012). Around 90% of irrigated rice in China was grown under continuous flooding or submerged soil conditions, consuming 65% of total amount of irrigation water and leading to large loss of water and thereby low water use efficiency (WUE) (Si et al., 2000). There is a large room for achieving high rice yield with less water input (Li et al., 2007; Tao et al., 2015).

Many water-saving methods had been developed to achieve the aims, such as alternative wetting-and-drying irrigation (Belder et al., 2004), dry-seeding technique (Tabbal et al., 2002), rice intensification system (Stoop et al., 2002), aerobic rice (Bouman et al., 2007) and ground cover rice production system (GCRPS) (Lin et al., 2002). Among those techniques, the GCRPS cultivation significantly helped extend rice growing areas, especially for those prone to drought or low temperature (Lin et al., 2002). High resource use efficiency in GCRPS was often considered to be related to the increased soil temperature, soil moisture and weed inhabitation (Li et al., 2007; Tao et al., 2015). Li et al. (2007) and Zhang et al. (2008) reported that GCRPS increased WUE and maintained high yield, compared to traditional flooding rice system. Furthermore, GCRPS might reduce greenhouse gas emission and have a significant advantage on water-saving, increasing the ground tem-

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perature and preventing water body pollution (Xu et al., 2004; Gao et al., 2009).

Soil temperature and soil water content are two key factors for many soil biophysical processes and crop growth (Jones and Kiniry, 1987; Hansen et al., 1990). Soil temperature can affect crop phenology, canopy development, biomass and crop yield (Stone et al., 1999). However, high soil temperature can also lead to high soil evaporation, which is considered as water loss, i.e., non-productive water to crop growth. To reduce soil evaporation, plastic film mulching (FM) is often applied in the field, which would influence soil heat transfer, soil water movement and crop growth, especially at the early stage (Li et al., 2007; Xie et al., 2005; Wang et al., 2015). The FM can effectively reduce evaporation thereby saving water and improving WUE by up to 60% (Belder et al., 2007; Qin et al., 2015). However, there were large variations between regions and crop systems. As yet, there is limited information on soil heat transfer and water movement in GCRPS because measuring these in the field is laborious and time-consuming. Furthermore, the results from the field experiments are often only relevant to a specific climate condition and/or soil type. Hence, there is a need to combine the advantages of the soil-crop model and the data of field experiments, in order to provide guidance for improving field management.

Many models have been used for rice production systems (Belder et al., 2007; Feng et al., 2007; Kadiyala et al., 2015). For example, Belder et al. (2007) used the ORYZA2000 model to identify the best irrigation regime in Hubei Province, China. Feng et al. (2007) explored the options to growing rice using less water in northern China based on the ORYZA2000 model, and found that wetting-and-drying irrigation can reduce 40–70% of water input without yield loss compared with flooding irrigation. Gaydon et al. (2012) coupled the ORYZA2000 model with soil water and nutrient modules from APSIM, and the model performed equally well in simulating rice grain yield compared to the original ORYZA2000. Kadiyala et al. (2015) used DSSAT (CERES-Rice) model to develop the best management practices (BMPs) for rice-maize cropping system, the results showed that BMPs can save 41% of water input and produce 96% of the yield attainable under conventional management. Chun et al. (2016) assessed the impacts of climate change on rice yields in Southeast Asia to make recommendations for national- and farmer-level adaptation strategies appropriate to different stakeholders. These studies mainly concentrated in the flooded rice planting patterns, However, few have considered the changes of soil temperature and evaporation under FM system. Moreover, most soil-crop system models could not simulate the effect of FM on soil heat transfer, water movement and crop growth for GCRPS due to lack of quantitative method and measured field data.

To quantify the effect of FM on crop growth, it is necessary to improve the existent soil-crop system models for simulation of the change of both soil temperature and soil water content under FM condition simultaneously. Han et al. (2014) modified soil heat module of DNDC (Denitrification-Decomposition) to assess the impacts of FM on regional maize yield in Northern China. However, the modified DNDC model was mainly designed to simulate soil temperature and soil water content in dryland, which is not suitable to GCRPS. Recently, an integrated soil-crop model (WHCNS, soil Water Heat Carbon Nitrogen Simulator) was developed to optimize water and N management (Hu et al., 2007; Liang et al., 2016a). The model can simulate water movement, heat transfer and nitrogen transport under a double-cropping production system in the North China Plain (Li et al., 2015a). But the model is unable to simulate the effect of mulching on soil heat transfer, water movement and crop growth under GCRPS.

Therefore, the objectives of this study were to (i) improve the soil water and heat modules of WHCNS model to simulate soil temperature, water content and crop growth in GCRPS in mountainous region of Central China, and (ii) to analyze the effect of film mulching on water balance and WUE, and identify the optimal management practice among different water and N treatments.

2. Materials and methods

2.1. Study area

The experiment was conducted at a farm (32°07′N, 110°43′E, and 440 m ASL) in Fangxian County, which is located in the mountainous region of Hubei Province in Central China. There are two major concerns in the local rice production: seasonal water shortage and low temperatures at the beginning of the rice growth season (Tao et al., 2015). The FM has been reported as one of the most effective measures to solve these problems in this region (Lin et al., 2002; Li et al., 2007). The soil was a silt loam with a texture of 20.3% sand (0.05–2 mm), 60.0% silt (0.002–0.05 mm) and 19.8% clay (<0.002 mm) and in the 0–20 cm depth layer it had 21.3 g organic matter kg^{-1} and 1.31 g total N kg^{-1}. The mountainous region of Fangxian County is exposed to northern subtropical monsoon climate, with an annual mean air temperature of 14.2 °C and an annual average rainfall of 830 mm. The total annual sunshine hours are 1850 ± 150 h and the frost-free period lasts 225 ± 15 days.

2.2. Experiment design and filed management

The experiment was conducted over two rice growing seasons (late April-September) in 2013 and 2014. Six experimental treatments were designed (consisting of two water management combined with three N treatments). Two water treatments were: (1) W_{sat}, mulched with plastic film and soil water content was kept approximately saturation from transplanting until two weeks before harvest; and (2) $W_{80\%}$, mulched with plastic film and average soil water content in root zone (0–50 cm) was kept between 80% and 100% field capacity based on the measured soil water content every two days, water balance method is used to calculate the irrigation amount. Three N treatments were designed: (1) N1: zero-N fertilizer; (2) N2: 150 kg urea N ha^{-1} given as basal fertilizer; and (3) N3: 75 kg urea N ha^{-1} plus 75 kg N ha^{-1} as chicken manure, all applied as basal application. All treatments received the same amount of phosphorus (45 kg P_2O_5 ha^{-1} as $Ca(H_2PO_4)_2$) and potassium (45 kg K_2O ha^{-1} as KCl). All treatments were set up in a randomized block designed with three replicates, each plot was 9 m wide by 10 m long as illustrated in Fig. 1. Seedlings were transplanted on 28 April in 2013 and 2014. Harvest was done on September 10, 2013 and September 19, 2014. Details of the irrigation and fertilization can be found in elsewhere (Tao et al., 2015; Jin et al., 2016).

2.3. Observations and measurement methods

Soil samples were collected from a soil profile up to 0.8 m depth for the analysis of basic physicochemical properties (Table 1). The temperature of topsoil (5 cm) was measured hourly by a thermistor sensor (EBI-20T, Ebro Instruments, Germany), soil profile temperature (10 and 20 cm depth) were measured hourly by a thermocouple sensor (CB0221, Edison state of Beijing scientific instrument co., LTD, China). The soil volumetric water content was measured every two days at 0.20 m's interval up to 0.8 m of soil profile, using a capacitance based soil moisture sensor (Diviner 2000, Sentek, Australia).

Crop dry matter and leaf area index (LAI) were measured at the stages of middle tillering, maximum tillering, panicle initiation, flowering and maturity. On each sampling date, 8 hills (0.4 m^2) were harvested. Plant samples were washed with distilled water