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Sustainable intensification options to improve yield potential and eco-efficiency for rice-wheat rotation system in China

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ABSTRACT

Agricultural production systems are facing the challenges of increasing food production while reducing environmental cost, particularly in China. To improve yield potential and eco-efficiency simultaneously for the rice-wheat rotation system in China, we investigated changes in potential yields and yield gaps based on the field experiment data from 1981 to 2009 at four representative agro-meteorological experiment stations, along with the Agricultural Production System Simulator (APSIM) rice-wheat model. We further optimized crop cultivar and sowing/transplanting date, and investigated crop yield, water and nitrogen use efficiency, and environment impact of the rice-wheat rotation system in response to water and nitrogen supply. We found that the yield gaps between potential yields and farmer's yields were about 8101 kg/ha or 45.3% of the potential yield, which had been shrinking from 1981 to 2009. To improve yield potentials and eco-efficiency, the cultivars of rice and wheat that properly increase both radiation use efficiency and grain weight are promising. Rice cultivars breeding need to maintain the length of panicle development and reproductive phase. High-yielding wheat cultivars are characterized by medium vernalization sensitivity, low photoperiod sensitivity and short length of floral initiation phase. Proper shift in sowing date can alleviate the negative effect of climate risk. Intermittent irrigation scheme (irrigate until surface soil saturated when average water content of surface soil is < 50% of saturated water content) for rice, together with nitrogen application rate of 390–420 kg N/ha (180–210 kg N/ha for rice and 210 kg N/ha for wheat), is suggested for the rice-wheat rotation system to maintain high yield with high resource use efficiency. This suggested nitrogen application rates are lower than those currently used by many local farmers. Our findings are useful to improve yield potential and eco-efficiency for the rice-wheat rotation system in China. Furthermore, this study demonstrates an effective approach with crop modelling to design farming system for sustainable intensification, which can be adapted to other farming systems and regions.

1. Introduction

Rice and wheat are two vital cereal crops in China. But since 2000 the growth rates of rice and wheat yields have become stagnated in some major production areas of China (Ray et al., 2012; Xiong et al., 2015; Wei et al., 2015). Owing to cultivar renew and agronomic management improvement, farmer's yields have increased notably and become closer to the potential yield in past three decades (Li et al., 2014; Bai et al., 2016). To meet the increasing food demands in future, sustainable intensification of agricultural production system to improve agronomic management practices and increase yield potential is essential. Among other things, cultivar improvement is one of the important options to adapt to climate change and increase yield potential (Yoshida et al., 2015). The increase in crop yield potential over the past decades was largely due to a gradual combination of cultivar traits related to high yield potential (Chang et al., 2016). To develop new cultivars, a large number of field experiments are needed to test the performance of new cultivars under different conditions. However, these experiments are time- and resource- consuming and are not suited to evaluate the performance of many cultivars (Fukui et al., 2015). Instead, crop simulation model provides an opportunity to evaluate the performance of a large number of cultivars under different climatic and management conditions.

Besides crop cultivar, optimal agronomic management practices,

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such as the optimal sowing/transplanting date, the optimal nitrogen and irrigation application rate, are the key options for agricultural sustainable intensification (Cassman et al., 2003). Deviation from the optimal sowing/transplanting time may result in incomplete panicle exertion and increased spikelet sterility (Magor, 1984). This deviation could influence crop growth and yield because of temperature fluctuation during crop growth period (Ehsanullah Anjum et al., 2014). Shifting sowing/transplanting date is an effective adaptation strategy for crop to cope with ongoing climate change (Tao et al., 2012). It is effective to optimize sowing/transplanting date to prevent crop from damage by high temperature, pests and diseases. Nitrogen is one of the most essential nutrients for crop production. In most cases, applied nitrogen fertilizer is not used efficiently, and only 35% or less is taken up by crops, particularly in China (Zhu and Chen, 2002). A large amount of N fertilizer is lost to environment which results in degradation of water and soil quality, high incidences of pest and diseases, and reduction of crop yield (Guo et al., 2010; Alam et al., 2011; Liu et al., 2013b). Irrigation scheme could be another possible reason for using nitrogen inefficiently (Deihimfard et al., 2015). Inappropriate irrigation amount and timing could result in draining high amount of water and losing high amount of nitrogen through leaching. To meet the demands of increasing crop yields and protecting environmental quality simultaneously, it is necessary to optimize management practices to increase water and nitrogen use efficiency (Liu et al., 2013a; Chen et al., 2014).

In order to explore the new technology to optimize agronomic management practices and improve crop yield potential, crop models are widely use to quantify crop potential yield and yield gap (Neumann et al., 2010; Wang et al., 2014; Lv et al., 2015). Since 1990, crop simulation model has become an important tool of crop breeding owing to its advantage in simulating the interactions between genotype, environment and management (Dingkuhn et al., 1991; Tardieu, 2003; Hammer et al., 2006). In crop models, crop cultivar is defined as a set of cultivar parameters related to growth and development of a crop with the given environmental conditions (Rötter et al., 2015). By changing parameters from given value ranges and optimizing them in response to environment conditions, the optimal cultivar can be identified that showed best yield performance under given environment conditions (Semenov et al., 2014; Tao et al., 2016). In addition, several studies showed that the calibrated and validated crop model could estimate crop yield, crop water and nitrogen uptake in response to water and nitrogen supply (Chen et al., 2010a,b), therefore crop modelling has been intensively used to explore strategies for increasing water and nitrogen use efficiency of farm system (Holzworth et al., 2014; Zhao et al., 2015).

Most of previous studies focus on crop yield potential and resource use efficiency of mono-cropping system, but the studies on the crop rotation system are scare, especially for the rice-wheat rotation system in China. In this study, using field experiment data from 1981 to 2009 at four representative agro-meteorological experiment stations (Fig. 1), together with the APSIM rice-wheat model, we aim to (1) estimate the potential yield and yield gaps of the rice-wheat rotation system; (2) optimize crop cultivar and sowing/transplanting date for the rice-wheat rotation system; (3) optimize the sustainable intensification options for the rice-wheat rotation system through investigating the crop yield, resource use efficiency and environment impact in response to water and nitrogen supply. We try to put forward with a full set of sustainable intensification options to improve the yield potential and eco-efficiency for the rice-wheat rotation system in China. These include increasing potential yield, closing yield gaps, optimal crop cultivar traits, optimal sowing/transplanting date, and optimal irrigation and nitrogen application rates, instead of addressing the issues separately as in many previous studies.

2. Materials and methods

2.1. Study sites, climate, crop and soil data

Four agro-meteorological experiment stations with contrasting climatic and geographical conditions, and good trial data in the southern part of Huang-Huai-Hai plain of China were selected in this study, including Hefei and Shouxian stations in Anhui province and Kunshan and Xuzhou stations in Jiangsu province (Fig. 1). Rice-wheat rotation system is the dominant cropping system in the study region. During rice growth period, average daily maximum and minimum temperature ranged from 28.2 to 28.7 °C and from 19.4 to 22.0 °C, respectively; total precipitation ranged from 558 to 700 mm across the stations. During wheat growth period, average daily maximum and minimum temperature ranged from 13.9 to 15.0 °C and from 4.3 to 6.6 °C, respectively; total precipitation ranged from 224 to 496 mm across the stations (Table 1).

Daily weather data at the study stations from 1980 to 2009 were obtained from the Chinese Meteorological Administration (CMA), including minimum and maximum temperature, sunshine hours and precipitation. Daily solar radiation was calculated from daily sunshine hour based on the Angstrom equation (Prescott, 1940). Crop trial data for the rice-wheat rotation system at the four study stations, including cultivar type, crop phenological stages, yield and yield components, county average yield, and agronomic management practices, were obtained from the CMA. Crop management practices at the stations were generally same as or better than the local farmer's practices (Tao et al., 2014). In this study region, continuous flood irrigation was applied to rice, but wheat was rain-fed. Soil data for the four study stations were obtained from the second national soil survey data (National Soil Survey Office, 1994), including the soil bulk density (BD), lower limit of plant extractable water content (LL), water content at drained upper limit (DUL), saturation water content (SAT), soil organic matter, soil total N and soil pH for each soil layer. The soil profile for each station is representative of the dominant soils for the area around the station (National Soil Survey Office, 1994). Detailed soil profile information is given in Table 2.

2.2. APSIM rice-wheat rotation system model

The APSIM model was applied to simulate potential yield and optimize cultivar, irrigation, nitrogen application rate and sowing/transplanting date of the rice-wheat rotation system in this region. APSIM is a component-driven model that simulates crop growth and development, yield, soil water and nitrogen dynamics either for single crop or crop rotations in response to climatic and management changes on a daily time step (Holzworth et al., 2014). APSIM rice-wheat rotation system model consists of two sub-models: APSIM-oryza model (Gaydon et al., 2012a,b) and APSIM-wheat model (Wang et al., 2003). APSIM has been widely used to simulate yield, crop water and nitrogen uptake of rice and wheat in response to water and nitrogen input in many countries, including China (Xiao and Tao, 2014; Gaydon et al., 2017). To simulate the potential yield of the rice-wheat rotation system, the modern cultivar parameters for the period of 2005–2009 (00s) at each station were used, which were calibrated and validated in Bai et al. (2016). In all simulations, the maximum root depth of rice and wheat was set to 30 cm and 100 cm, respectively.

2.3. Estimates of potential yield and yield gaps

Potential yield is defined as the highest yield of a modern high-yielding cultivar achieved under favorable conditions without growth limitations of water, nutrient, pests and disease (the yield is only affected by climatic conditions) (Lobell et al., 2009). Farmer's yield is the average yield achieved by farmers (the average yield for the county around each station is set to farmer's yield). For the rice-wheat rotation