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Adaptation of paddy rice in China to climate change: The effects of shifting sowing date on yield and irrigation water requirement

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ABSTRACT

Warming and increasing extreme climate events are expected to reduce crop yields including rice production in China, threatening the Chinese food security. Shifting sowing date has been considered as a key adaptation strategy to sustain rice production in China. However, the extent to which it can mitigate the adverse climate change impact on yield and whether more irrigation is required remains unclear. Here, by driving ORYZA v3 with four climate models (GCMs), we analyzed the impacts of climate change on China rice yield and net irrigation water requirement (NIR) at 21 sites under a wide range of sowing date. We found that without altering sowing date, weighted average rice yield for all sites will decline 5.1, 7.3 and 15.1% in periods 2011–2040, 2041–2070 and 2071–2100, respectively. Yields losses in temperate zones are linked to increased crop development rates with higher temperatures, but in subtropical regions, the reduction is more related to the damage of heat stress during rice heading or flowering periods. NIR increases notably in all regions (up to 71%) except northeastern China, where the shortened growth duration resulted in less time to consume water. When the optimized sowing date is applied, average yield losses will be effectively compensated. To achieve these, rice-sowing date will be shifted by up to 54 days and on average 17.8–23.4 % more fresh water in future periods are needed to meet the water requirement of rice growth. We also found that, due to increasing the frequency of heat events, farmers in Chinese rice production regions (e.g., Yangtze River Basin) will have narrow sowing windows at the end of this century. This study suggests that adequate irrigation and adjusting sowing dates could mitigate the negative climate impacts on rice production in China.

1. Introduction

Rice is the most important cereal crop grown in China, nearly one billion people depend on it as their staple food (Tao et al., 2013). However, its sustainable production is being faced with many challenges, including labor shortage (Shen et al., 2011), the need to reduce greenhouse gas emissions such as CH_4 (Zhang et al., 2016), and the competition for paddy land and water resources from non-agricultural sectors (Challinor et al., 2014). Furthermore, climate change, mainly characterized by increased temperature, shifted rainfall patterns, and more frequent extreme climate events (Piao et al., 2010), has not only dramatically altered the climate condition (Godfray et al., 2010; Shen et al., 2011; Wang et al., 2014), but also threatened the stable supply of irrigation water resources (Sun and Yang, 2012; Zhang and Zhou, 2015; Cao et al., 2017). Therefore, it is imperative to project the future impacts of climate change on Chinses paddy rice production and water consumption, and further explore potential adaptation strategies.

Climate change without adaptation is projected to influence crop growth and water use in a number of ways. The elevated temperatures have been known to accelerate the growth process of most crops, resulting in less time for biomass accumulation (Tao et al., 2008; Hawkins et al., 2013; Zheng et al., 2012). On the other hand, short periods of extreme high temperature during key crop growing stages such as flowering and grain filling are associated with dramatic yield loss by reducing the potential grain number or increasing the proportion of shrunken grains (Ciais et al., 2005; Fuller et al., 2007; Butler and Huybers, 2013). Apart from affecting crop yield, warming also has many influences on crop water use, including the acceleration of crop evapotranspiration rate at a higher temperature, as well as the shortened crop growing duration for water consumption (Wang et al., 2014;

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Zhao et al., 2015; Ding et al., 2017). Owing to the adequate irrigation, rice production in China is not easily threatened by drought, but in recent years, climate change has dramatically shifted the precipitation pattern in south China, the main rice planting region, causing severe shortages of available irrigation water resources (Tan et al., 2017; Hu et al., 2017; Xiao et al., 2018). Unlike the adverse impacts of temperature increase and precipitation variation, the increasing CO_2 concentration is known to have positive effects on crop production. Elevated CO_2 is anticipated to improve crop yield through expressing higher thermotolerance of photosynthesis, which is especially the case for C3 crops such as rice and soybean (Taub et al., 2000; Chapin et al., 2011; Jin et al., 2017). Moreover, by increasing crop stomatal closure, elevated CO_2 leads to decreased crop transpiration rate, thus benefiting the reduction in irrigation water requirement (Tao et al., 2008; Elliott et al., 2014; Deryng et al., 2016; Wang et al., 2017a).

Expanding cropping area, shifting sowing date, switching to new varieties, further optimizing the using of water and fertilizer are strategies to cope with climate change for sustaining crop production (Lobell et al., 2008, 2015; Rurinda et al., 2015). However, the current situation of rice production system in China may limit the application of the most aforementioned adaptive strategies. Since the Han Dynasty (202CE –220CE), to feed the growing population, Chinese people have exploited most of the arable land to maximize food production with intensive labor, water and fertilizer inputs, which is known as "Intensive and Meticulous Farming". Today, with the help of modern irrigation systems, widely distributed fertilizer plants and high-yield hybrid varieties, this intensive farming system has helped to close the yield gap between realized and potential (Peng et al., 2009). Statistical data showed that China provides 27.8% of global rice production within only 18.57% of its planting area (FAOSTAT, 2018). In other words, under a changing climate and rising food demand, most of the common adaptation strategies lost their brilliance with this farming system, as yield cannot be easily increased by reducing water deficit and more fertilizer use or expanding arable land like Africa and Southeast Asia did, where the shortages of water and nutrients are the main limitations in their rice production (Lobell., 2008). Shifting sowing date, a low-cost and easy-implement strategy (Waongo et al., 2015; Rurinda et al., 2015), is thus the key adaptation strategy, which can allow crop growth to occur in the periods with more suitable climate conditions (Zheng et al., 2012).

Irrigation, the most paramount factor to maintain the high rice yield in China, and by far the largest component (ab. 54%) of national total anthropogenic fresh water consumption (Wang et al., 2017b), is expected to change significantly under the combined effects of climate change and shifted sowing date, raising concerns regarding whether water resources shortage will be a limiting factor for rice production under future optimized sowing date (Elliott et al., 2014; Ye et al., 2015; Ding et al., 2017). For instance, although earlier sowing date in northeast China may be beneficial to rice yield, the critical water consumption period such as heading may miss the rainy season, resulting in a sharp increase in the amount of water needed for irrigation. It also should be noticed that future available irrigation water resources could be limited by the increasing water consumption from non-food uses (Challinor et al., 2016; Wang et al., 2013; Samani et al., 2018). Statistical evidence has been showed that due to the shortage of irrigation water resources, rice cultivation area in the North China Plain has decreased dramatically in the past 30 years (National Bureau Statistics of China, 2014; Gao and Luo, 2008). Therefore, the projection of rice irrigation water requirement under the shifted sowing date is of significant implications for both food security and water security.

Process-based crop models that can simulate the interactions between multiple environmental factors and management practices are useful tools to assess the impacts of climate change on crop growth and explore potential adaptation strategies (Boote et al., 1996; Keating et al., 2003; Van Oijen and Lefelaar, 2008; Chenu et al., 2011; Zhao et al., 2016; Liu et al., 2016). By using the crop models, extensive studies have attempted to evaluate the potential impacts of future climate change on rice yield (i.e., Yao et al., 2007; Xiong et al., 2009; Tao et al., 2008; Shen et al., 2011; Wang et al., 2014, 2017a; Xu et al., 2015; Li et al., 2016; Zhang et al., 2017). However, to our knowledge, existing modeling studies have neither given an explicit answer to the extent to which shifting sowing date can offset the impacts of climate change on rice production, nor given how the corresponding irrigation water requirement would change. More efforts are thus needed to explore the potential adaptation and its impacts on water consumption, in order to inform future rice breeding and water resources utilization.

In this study, the ORYZA v3 crop model (Bouman et al., 2001; Li et al., 2017) driven by four bias-corrected global climate datasets at 21 agricultural experimental sites spanning the main rice production regions in China was used to investigate the comprehensive impacts of climate change and shifting sowing date on rice yield and water consumption in China. The following four questions were addressed: (1) how does climate change affect the yield and NIR on Chinses paddy rice under current field management practices and cultivar choices? (2) How will the sowing date be adjusted to optimize rice yield? (3) To what extent can changing planting date mitigate the negative effects of climate change on rice yield? and (4) How will the corresponding NIR change under the altered sowing date?

2. Materials and methods

2.1. Study site and experimental data

Twenty-one Agro-meteorology Experimental Sites (AES) spanning the main China rice growing regions from temperate zone to south subtropical zone were studied (Fig. 1). These sites were maintained by China Meteorological Administration (CMA) and purposefully selected to represent different rice types (single, early, and late rice) and different rice planting regions classified by Mei et al. (1988). Generally, single rice is cultivated in southwestern China and the north of the Yangtze river, where rice is sown between March 10^{th} and June 15^{th}, while double rice (rotation between early and late rice) is the typical cropping system in the south of the Yangtze river, with early rice and late rice sown around March 20^{th} and July 5^{th}, respectively. However, due to the short of labor force or rotation with other crops such as sugarcane (Shen et al., 2011), farmers in the double rice cultivation regions might only breed early or late rice in one year. Thus, early and late rice sites in Guangxi and Fujian provinces are not at the same location (Fig. 1).

Historical data of rice phenology (i.e., sowing, transplanting, flowering, maturity dates), yields and management practices from 2002 to 2012 were extracted from the AESs. These experiment data were collected based on a uniform CMA observation standards and guidelines (Liu et al., 2012).

2.2. Current and future climate data

To quantify future climate and its uncertainty impacts, a number of climate projections from General Circulation Models (GCMs) were used (Xing et al., 2014; Rurinda et al., 2015; Lobell et al., 2015). Specifically, future climate data from 2011 to 2100 were obtained from four GCMs including HadGEM2-ES, BCC-CSM1.1 (m), MIROC-ESM-CHEM, and GFDL-ESM2M (see Table S1), participating in the coupled model intercomparsion project phase 5 (CMIP5, Taylor et al., 2012). We considered these four GCMs because they fully meet the data required to simulate rice yield and paddy water balance at the same time and were widely used in climate change studies in China (e.g., Yin et al., 2015; Guo et al., 2015; Wang et al., 2017a). Four representative concentration pathways (RCP2.6, 4.5, 6.0 and 8.5) were released by CMIP5 (Taylor et al., 2012), but we only focus on the high concentration pathway (RCP 8.5) for which radiative forcing rise to 8.5 W m^{-2} by 2100.

Historical daily climate data including minimum and maximum

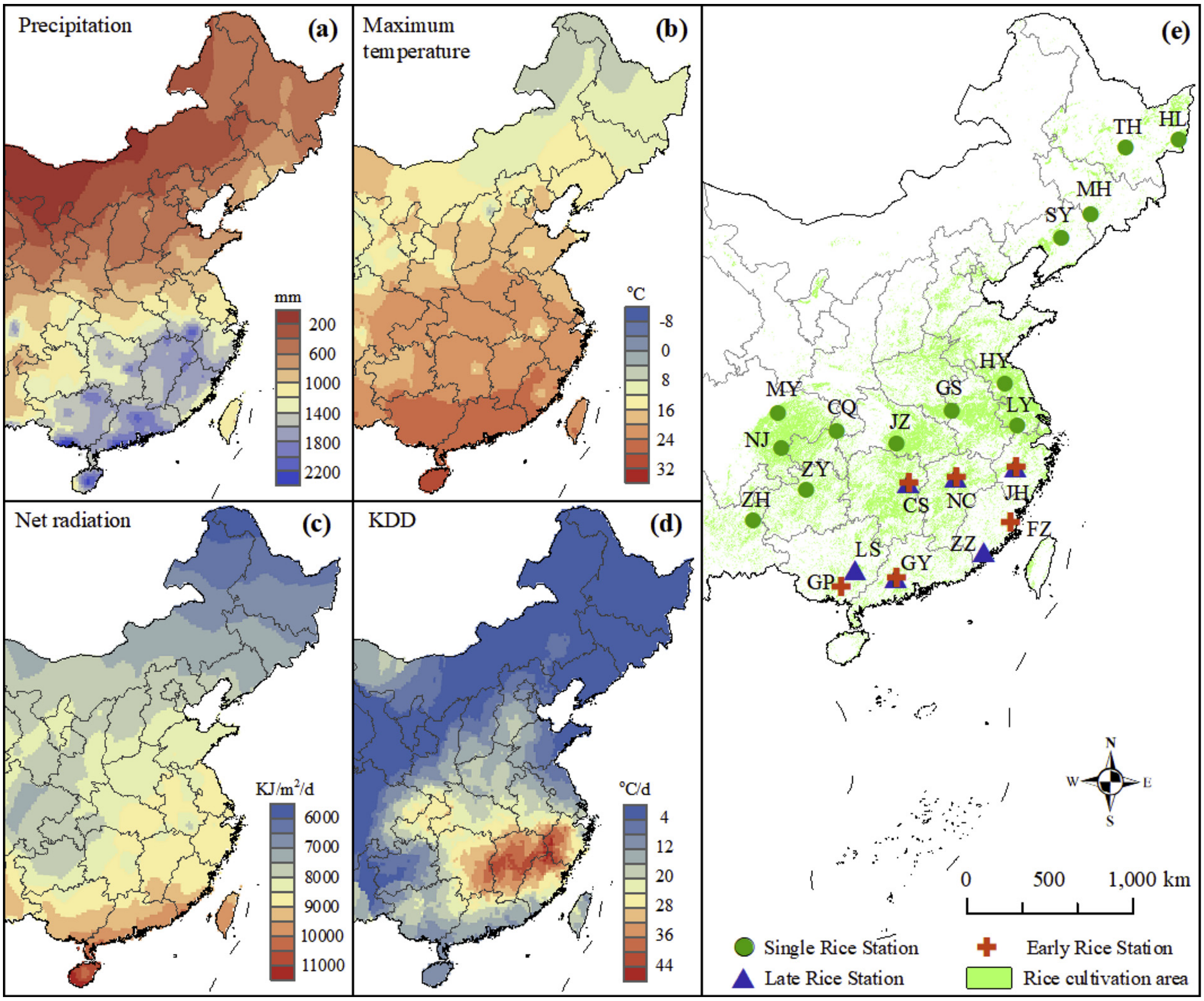

Fig. 1. Study sites and their weather condition of baseline period in China: (a)-(d): average cumulative precipitation, daily maximum temperature, daily net radiation, and killing degree days (KDDs) in the baseline period (1981–2010). KDD is a commonly used measure for the cumulative heat damage a crop has experienced, here defined as the sum of daily maximum temperature over 35 °C. (e) rice-growing area sourced from International rice research institute and the locations of the 21 sites where the climate change impacts and adaptation were analyzed.

temperatures, sunshine duration, relative humidity, wind speed, and precipitation from 1976 to 2013 at each site were obtained from National Meteorological Information Centre of China (NMIC) of CMA. To meet the data requirement to force crop model, sunshine duration and relative humidity were converted to solar radiation and actual vapour pressure using the method provided by Prescott (1940) and Allen et al. (1998), respectively.

The climate data were bias-corrected against the baseline observed data. The minimum and maximum temperature, solar radiation, wind speed, and vapour pressure data were corrected by quantile mapping (Li et al., 2010; Wang and Chen, 2013). The precipitation data were corrected with the method of Piani et al. (2010) that can reproduce extreme events and eliminate excessive number of occurrences of drizzle. It should be specially noticed that, although the ensemble of multiple GCMs improves the projection of climate data, aggregating of many climate models directly could shift climate patterns, for instance, bringing more wet days and less extreme precipitation. Therefore, in this study, we drive the crop model with the individual GCM outputs and then average the simulation results across the four GCMs.

2.3. Crop model description

Rice yield and irrigation water requirement in response to future climate change and shifting planting date were simulated using ORYZA v3 (https://sites.google.com/a/irri.org/oryza2000). ORYZA is an advanced, dynamic eco-physiological model jointly developed by International Rice Research Institute (IRRI) and Wageningen University (Karim et al., 2012). Driving by weather, soil, crop, and management data, the model simulates rice yield, growth stage, dry matter distribution and water balance, under water stress, nitrogen stress and N × W stress conditions on a daily basis. ORYZA v3 has a detailed water balance module, which allows the users to set up complexed irrigation schemes in modeling experiments (Bouman et al., 2001). The model is also more suitable to simulate NIR of lowland rice than other models such as CERES-Rice and WOFOST. Meanwhile, the performance of ORYZA has been widely validated against the experimental data in a wide range of climate regions in Asia (e.g., Karim et al., 2012; Shen et al., 2011; Li et al., 2013; Yuan et al., 2017). In recent years, ORYZA has been successfully applied in China to evaluate the options to grow rice with less water (Bouman et al., 2007), investigate the impacts of climate change on rice production (Wang et al., 2014) and irrigation (Luo et al., 2015), and monitor large-scale rice growth and development by combining remote sensing data (Setiyono et al., 2012; Pazhanivelan et al., 2015).

The accurate simulation of rice growth period duration (GPD) is crucial for this study since warming over rice growing season causes yield change primarily through its effects on the length of life cycle. Furthermore, NIR is also highly related to crop life cycle (Zhao et al.,

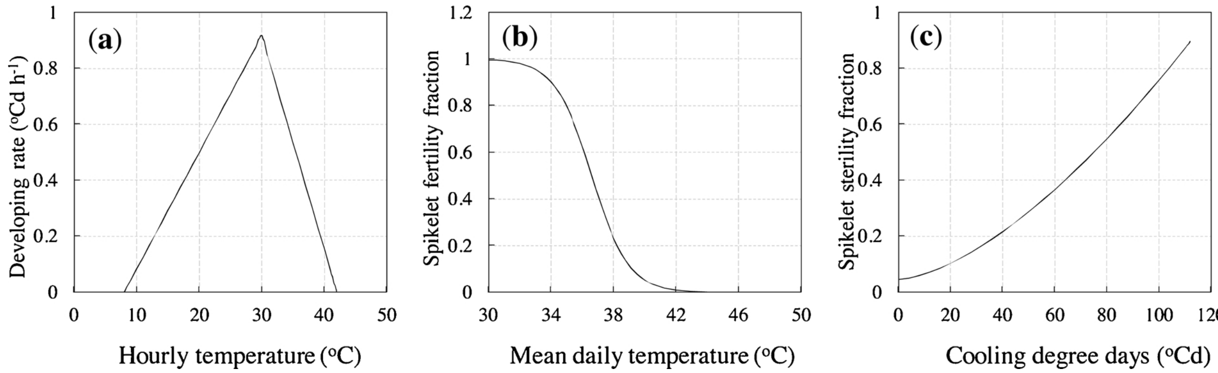

Fig. 2. The main response functions to simulate the direct and indirect effects of temperature increase on rice yield and irrigation. (a) Relationship between hourly temperature and developing rate. (b) Relationship between mean daily maximum temperature during the flowering period (0.96 < DVS < 1.22) and spikelet fertility fraction. (c) The influence of cooling degree days on spikelet sterility fraction during booting and flowering periods (0.75 < DVS < 1.2).

2015). In ORYZA v3, the development stage (DVS), indicating rice physiological age, is calculated based on hourly increments in heat units (*HUH*, °Cd h^{-1}). The response of temperature to *HUH* is simplified as a linear function (Fig. 2a). For temperature below the base temperature (*TBD*) or higher than the maximum temperature (*TMD*), rice development will stop, while temperature equals the optimum temperature (*TOD*), rice grows fastest. In this study, the values of these three cardinal temperatures (TBD, TOD and TMD) are 8, 30, and 42 °C, respectively (Gao et al., 1992).

Apart from the length of rice life cycle, spikelet sterile, the key factors related to rice yield losses, are also sensitive to extreme high or low temperatures (Horie et al., 1992). The cooling degree-days (COLDTT; °Cd) during rice panicle stage (0.75 < DVS < 1.2) is used to evaluate the impacts of cold temperature on sterility, while the average daily maximum temperature (TFERT; °C) over flowering period (0.96 < DVS < 1.22) is adopted to describe the relationship between high temperature and rice fertility (Bouman et al., 2001). According to Horie et al. (1992), when daily mean temperature is less than 22 °C or average daily maximum temperature during flowering period is higher than 35 °C, the percentage of rice spikelet fertility will be dramatically reduced (Fig. 2b and c).

Unlike the upland crops such as wheat and maize, rice cultivation in China is dominated by paddy field farming, the most water-intensive type of crop planting. In ORYZA v3, rice irrigation water requirement was determined by soil-water balance, which can be briefly described as:

$$dW = IR + R + C - E - T - S - P - D \quad (1)$$

Where dW is the change of field water stored; *IR* is irrigation water requirement; *R*, *C*, *E*, *T*, *S*, *P* and *D* represent precipitation, capillary rise, evaporation, transpiration, seepage, percolation and evapotranspiration, respectively. The irrigation scheduling (irrigation time and amount) is determined by the subroutine IRRIG, which provides five optional manners in which irrigation is applied and computes the daily amount of irrigation as a function of user-specified criteria. The five irrigation criteria are rained, irrigation supplied as input data, irrigation at critical ponded soil water depth, irrigation at critical soil-water tension, irrigation at critical soil water content and irrigation at X days after disappearance of ponded water.

2.4. Crop model simulation

To assess the impacts of climate change on rice production and water consumption and explore the potential adaptability, we first conducted the simulation for baseline (1981–2010) and three future periods (2011–2040, 2041–2070, and 2071–2100) under current sowing date. Subsequently, from 2011 to 2100, the simulation was carried out for planting dates at one-day intervals across a wide range of windows. The detailed information about current sowing date and growth duration for each site can be found in Figure S1. The sowing window for late rice was set to start from 150 Julian days of the year, because late rice is widely recognized as sowing after May (Huang et al., 2017). To consider the effects of CO_2 fertilization, the CO_2 concentration for future three stages were set as 449, 541 and 850 ppm, respectively. Besides, as nearly 95% of China rice production area is fully irrigated and fertilized, all of the simulations in this study were performed without any limitation on water and nitrogen. When computing region-wide aggregate statistics, the rice sites were weighted based on the rice production in the region (these weights are shown in Figure S2).

Soil data is highly related to deep percolation, a key element in water balance processes. However, for the following three reasons, soil data for all rice sites were set as default and daily soil percolation for each site was set as fixed value provided by a national-scale investigation (Chen et al., 1995). Firstly, unlike upland crops, soil percolation in paddy field is also highly related to non-soil type factors such as groundwater level, spacing of drainage ditches, and drainage depth. As a result, it is almost impossible to output an accurate percolation value by point-based crop model. Secondly, considering the great differences in soil properties in different regions, the large-scale investigation percolation values are more representative than point-scale simulation. Thirdly, as paddy field is always maintained with a certain depth of water, the percolation is almost constant during rice growing period. The fixed percolation value for each site can be found in Figure S3.

Due to the large differences in climate conditions, rice varieties vary obviously in different cultivation regions. For example, to adapt to the short growing window in northeastern China, rice life cycle in this region is usually less than 155 days, while in the warm southwestern China, rice life cycle can be longer than 170 days (Figure S1). Thus, in order to simulate the impacts of climate change on China rice production more accurately, we use site-specific cultivars and not one for all sites. For a specific site, observed phenological and yield data from 2002 to 2012 were divided into two groups. The data from odd years were used for calibration the cultivar parameters, while the rest experiment data were used for validation. Given the limitation of collected experimental data, we only adjust the most sensitive parameters to rice yield and water consumption such as phenology and dry matter distribution parameters (Luo et al., 2015), the other parameters were set the same as the experiment we carried out in our previous study (Wang et al., 2017a). This setting might bring a certain degree of uncertainty to the simulation results. Nevertheless, a recent study on crop model uncertainty showed that the uncertainty resulted from crop parameters is small when investigating changes in predictions and averaging over multiple years decreases the prediction bias by a wide margin (Wallach et al., 2016). With the help of two calibration

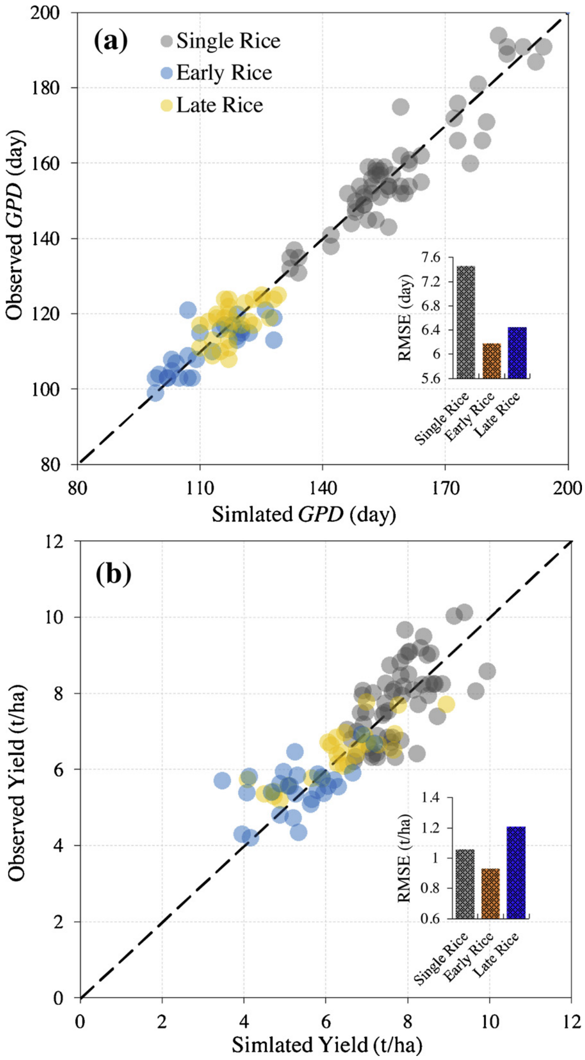

Fig. 3. Test of ORYZA v3 model for rice growth period duration (a) and yield (b) of single, early, and late rice at 21 sites. The observed maturity dates and yield data were extracted from China Meteorological Administration. The dashed lines correspond to the 1:1 line. The insert indicates the RMSE for rice yield and the length rice growth duration.

programs DRATES and PARAM that are built in the ORYZA, we calibrated rice genetic parameters at each site. Then, the calibrated model was driven with observed meteorology data from the even years to simulate crop yields and GPDs for validation. Fig. 3 showed the validation results of rice growth duration and yield at 21 sites. Simulated yield and growth duration for three types of rice are mostly in agreement with observational data from China Meteorological Administration. Deviations exist at some sites because experimental data are obtained with assumptions of no weeds, pests or other limiting factors.

3. Results

3.1. Projected climate change

Warming is roughly equal across the sites during rice growing season, although the mean temperature of the baselined period (1981–2010) varied largely among different regions. The average daily minimum temperatures (Tmax) over growing season for all sites were projected to increase by 0.8 °C in 2011–2040, 2.3 °C in 2041–2070, and 4.6 °C in 2071–2100 (Fig. 4a). By contrast, the directions of changes in projected growing season precipitation were less clear, but there was no significant change in the mean annual precipitation (Fig. 4b). The change of radiation was similar to that of Tmax, but with more distinct spatial variability. For example, in southern China, net radiation would increase on average of 7% during 2071–2100, while in northeastern China, 15% increment for the same period was found. Killing degree days (KDD), the sum of rice growing season maximum temperatures in excess of 35 °C, indicates the cumulative of heat events that might have adverse impacts on rice development. In the baseline period, apart from several sites (i.e., WX and JH) in the middle subtropical regions, most sites suffer less heat damages (KDD < 20 °C d), which is especially true for sites in northeastern China. In line with our study, Sun and Huang (2011) showed that global warming in the past 50 years did not enhance high temperature stress in heading-flowering stage for most China rice cultivation regions. However, analysis of future climate scenarios predicted large variations in the occurrence of heat events across the entire China rice cultivation region, ranging from locations still with negligible heat events (e.g., northeastern China) to locations with severe extreme hot days (e.g., north subtropical climate region) (Fig. 4d).

3.2. Impacts on rice yields and NIR under current sowing date

With the consideration of CO_2 fertilization, weighted average yields (the weight of each site can be found in Figure S2) will decrease 5.1, 7.3, and 15.1% in 2011–2040, 2041–2070 and 2071–2100, respectively (Fig. 5a). Among the single-rice sites, the largest yield decreases (30%) was found at WX in Sichuan Basin, which could be explained by the most severe heat damage it would experience (Fig. 4d). Compared to single rice, the mean yield losses for early rice were small, with the largest yield reduction of 14% occurring at JH during 2071–2100. Noticeably, slight yield increases were observed at three late rice sites (i.e., GY, GP and ZZ) and one single rice site (i.e., ZH) in 2011–2040 and 2041–2070.

Projected NIR for most sites would continue to increase in three future stages, but dramatically decreased NIR was also found (Fig. 5c). For single rice in northeastern China and Yunnan-Guizhou Plateau, NIR would decrease by up to 31% with the dramatically shortened rice growth duration, but at the rest single-rice sites, NIR would increase by up to 49%. For early rice, although the growth duration was shortened, NIR showed an obviously increasing trend with the value ranging from 21% to 71% in 2070–2100 period. Similar to that of early rice sites, increased NIR was observed across all late rice sites, while the increasing magnitude was relatively small (less than 19%).

3.3. Changes in yield and NIR under optimized sowing date

When the sowing date was shifted from current to the optimized date, yields increased notably for all sites in both near and long-term climates periods (Fig. 5a), especially for single rice in subtropical regions (i.e., JZ, GS, MY, WX), where the yield increase was even higher than 40%. While the yield increases in northeastern China (i.e., HL, TH) was small (less than 10%), resulting in that the optimized yield in this region was still lower than that over the baseline period. Similar to most single rice sites, early rice sites also showed dramatically yield increase under the optimized sowing date (up to 31%). However, the increase of yield for late rice was much smaller across most sites, among which the largest increase (11%) was observed at Zhangzhou (ZZ) in 2011–2040. In general, apart from northeastern China, shifting sowing date could effectively mitigate the negative impacts of climate change on China rice yield.

Under optimized sowing date, the increase to average NIR will be raised from 7.8, 6.3, and 10.9% to 17.8, 20.6, and 23.4% in 2011–2040, 2041–2070, and 2071–2100, respectively (Fig. 5c). For most sites, shifted sowing date prolonged crop water consumption time, reduced the synchronization of the key rice water consumption stage and precipitation period, resulting in a large increase in NIR (Fig. 5b and c).

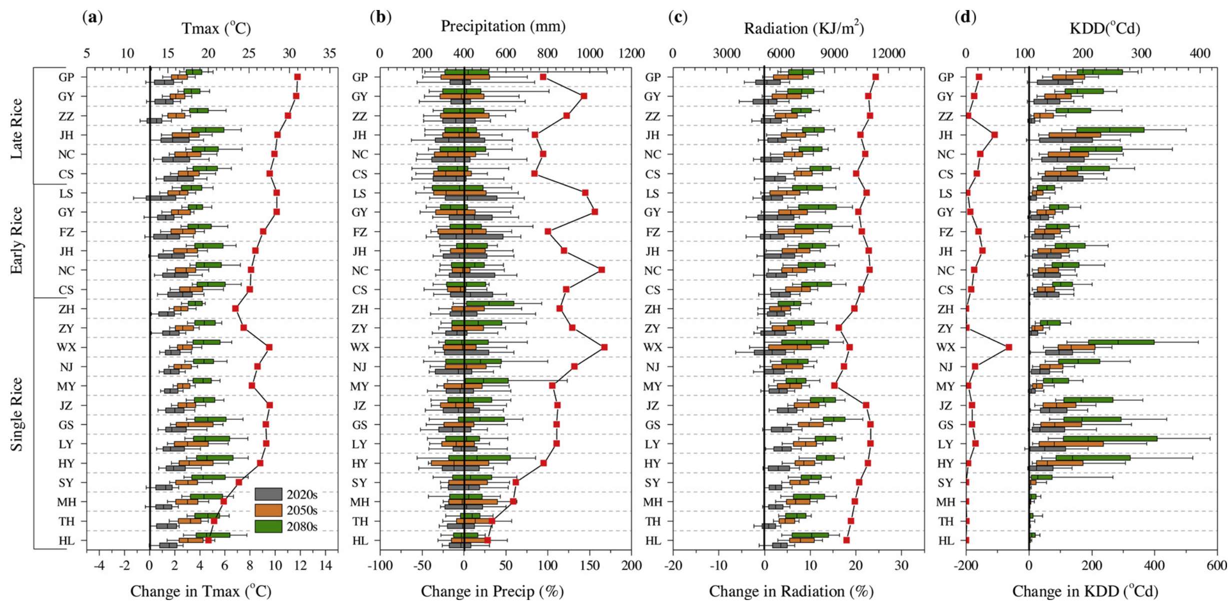

Fig. 4. Projected changes in averaged daily maximum temperature (Tmax), cumulative precipitation (Precip), global solar radiation, and killing degree days (KDD) for single, early, and late rice. The boxplot shows the variation of climate variables based on the ensemble of the four GCMs used in this study. The black lines with red dots indicate the mean values of climate factors for each site during the baseline period (1981–2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nevertheless, for several late rice sites (e.g., ZZ and GY), the NIR will be reduced to a certain degree because of the shortened rice growth durations.

3.4. The optimized sowing dates and sowing time windows

The optimal sowing date refers to the breeding date that rice yield could be maximized. Considering that rice breeding could be influenced by non-meteorological factors such as rotation with other crops or short of irrigation water resources, we also analyzed the potential sowing time windows to allow farmers sowing with more flexibilities. The possible sowing windows were defined as a group of planting dates that the corresponding yields are high than 90% of the maximum yield (see the examples in Figure S4).

The optimal sowing date would continue to advance up to 13, 32, and 37 days for 2011–2040, 2041–2070, and 2071–2100, respectively, at the four northeastern sites, where an early sowing date would provide relatively cold environment to slow down rice development rate to help dry matter accumulation (Fig. 6). While for the remaining single rice sites, to avoid the heat stress during key rice growing periods, sowing earlier or later was feasible (Fig. 6a). In case of early rice, the optimal sowing dates would be on average 15 days earlier in 2011–2040, 23 days in 2041–2070, and 28 days in 2071–2100 (Fig. 6b). However, the shift directions for late rice sites were not uniform, and the shift days were much shorter than the other two types of rice, especially at GY site, where the optimal sowing date would only be 5 days earlier in both 2041–2070 and 2071–2100 periods (Fig. 6c).

The start date of the potential sowing windows would be earlier at all single and early rice sites, but the lengths of these windows were much more complicated. In general, with temperature increasing, more dates are warm enough for rice growth. This is true for single rice in northeastern China, but it is too hot for rice flowering and heading in southern China in summer. Rice sowing windows in this region are thus divided into two separate narrow periods (Fig. 6a). For early rice, both the start and end days of the possible sowing windows are earlier, resulting in wider sowing windows for farmers (Fig. 6b). For late rice, the possible sowing windows started from Julian day of 150 but ended later with temperature increasing (Fig. 6c).

4. Discussion

Climate change will inevitably challenge the future production and water resource utilization of rice (IPCC, 2007; Piao et al., 2010; Wang et al., 2017a). Given the special rice production situation in China, shifting sowing date is anticipated to have an important role in mitigating the challenges of climate change on crop production (Lobell et al., 2015; Waongo et al., 2015). By using bias-corrected climate projections from multiple GCMs and the well-tested ORYZA v3 crop model, we explicitly assessed the impacts of climate change on growth duration, yield and net irrigation water requirement (NIR) of rice across China. This study for the first time evaluated the extent to which shifting sowing date could mitigate the negative effects of climate change on rice yield. We also investigated how NIR would change along with the shifted sowing date.

4.1. Climate change is predicted to affect China rice production and water utilization differently depending on the region

In temperate regions (e.g., northeastern China), in spite of the extended crop growth windows under the increasing temperature (Tao et al., 2008; Wang et al., 2012), rice growth duration was anticipated to decease for more than 30 days at the end of this century (Fig. 5). Along with the shortened growth duration, rice yields in these regions were reduced by up to 19%, as shortened rice life cycle dramatically reduced the available time for rice to acquire radiation, CO_2 and nutrients for biomass accumulation (Dennett, 1999; Springate and Kover, 2014). Other modelling studies also predicated the similar shortened growth duration for crops (Shen et al., 2011; Wang et al., 2014). For instance, a recent study showed that Australia wheat life cycle would anticipated to shorten by up to 42 days at 2050 (Zheng et al., 2012). Generally, this is a typical form of crop yield loss; most climate change related yield loss around the world could be explained by the shortened growth duration (Tao et al., 2008; Shen et al., 2011; Zhao et al., 2015). However, it should be noticed that although the magnitude of rice yield loss in subtropical regions was like that in temperate regions, rice growth duration was almost unchanged or even prolonged by up to 12 days at some sites (Fig. 5). This seems to be inconsistent with most previous modeling studies in this region (e.g., Shen et al., 2011; Wang et al.,

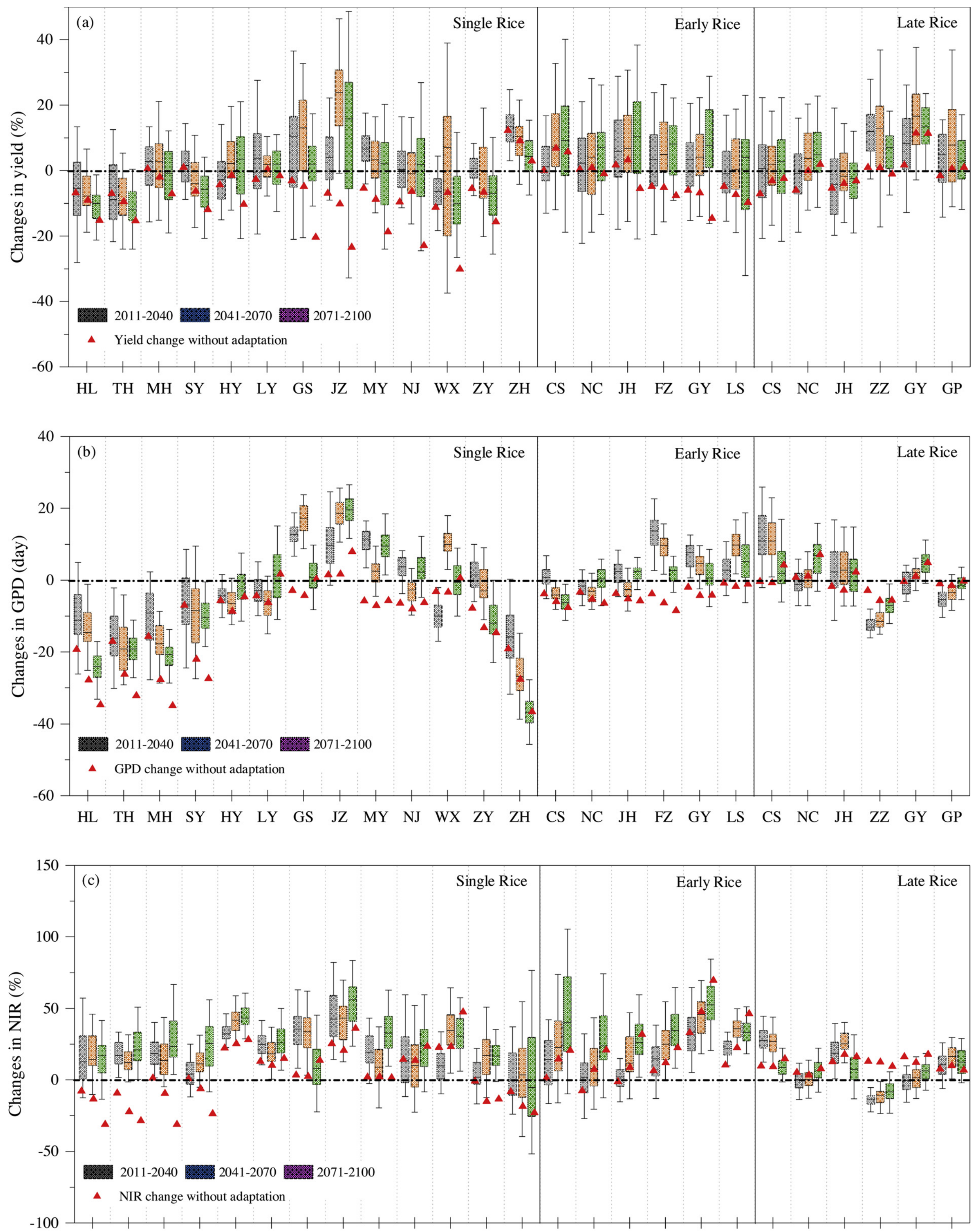

Fig. 5. Simulated yield, irrigation water requirement (NIR), and growth period duration (GPD) at current (red triangle) and optimum sowing dates (box plots) for each site. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2014). In fact, crop development rate would not accelerate continuously with temperature increase (Lu et al., 2008; Zhao et al., 2007), which is especially true for rice in subtropical regions, as the growing season temperature is close to or even exceeds the optimal development temperature during the baseline period (Fig. 4). Thus, yield loss for single rice in subtropical regions could be largely attributed to the dramatically increased heat events that occurred in the key rice growth stages (Fig. 4 and Fig. 7). It also needs to be noticed that although the average growing season temperature of late rice sites in south subtropical regions (i.e., Zhangzhou, Gaoyao and Guiping) was obviously

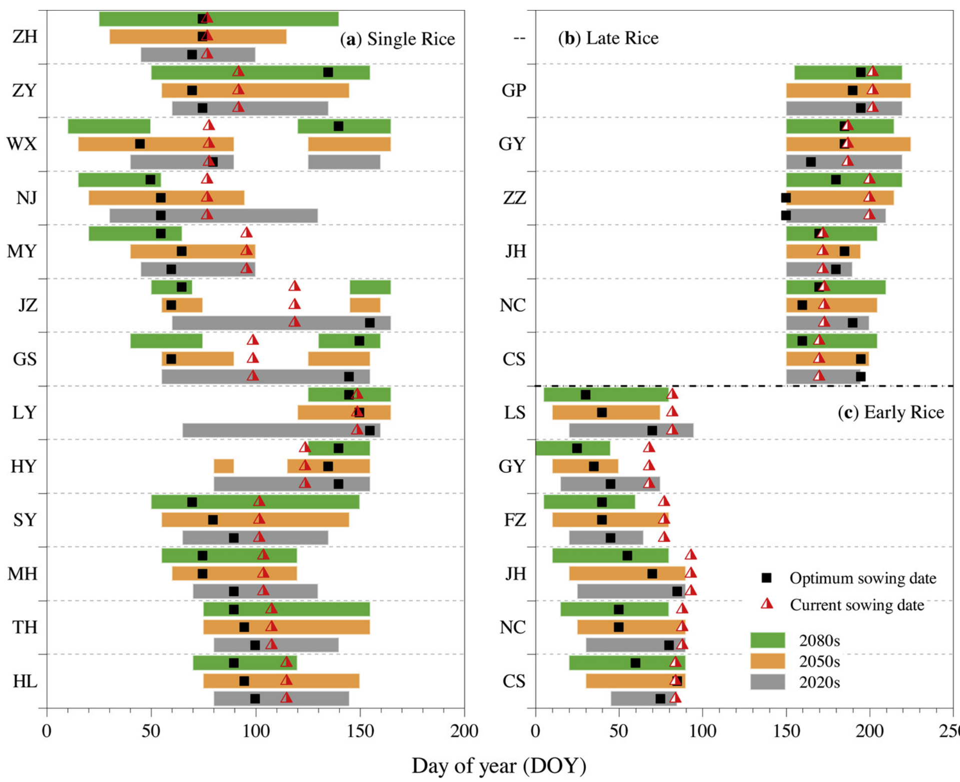

Fig. 6. Target sowing time windows (colored rectangles) and optimum sowing date (red triangles) for single, early, and late rice for future three stages under the RCP8.5 scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

higher than in other regions (Fig. 4), the yield of late rice in this region would increase by up to 10% (Fig. 5). A reasonable explanation is that the high temperature here slowed the rice development rate, resulting in a longer growth duration for biomass accumulation. Meanwhile, the late sowing date made the key rice-growing period avoid the extreme heat damage (Fig. 7).

The projected changes in net irrigation water requirement (NIR) differed notably across the different climate regions (Fig. 5), especially between temperate regions and subtropical regions, which was due to the large variations in the changes of growth duration. Warming shortened single rice growth duration more than 30 days in temperate regions, but much less so for rice in other regions. The shortened growth duration results in less time for rice to consume water by evapotranspiration. Therefore, although the elevated temperature and solar radiation could increase crop evapotranspiration rate, the notably shortened growth duration well explained the slightly reduced NIR for rice in temperate regions (Fig. 5). By contrast, under combined effects of prolonged rice life cycle, increased temperature and solar radiation, NIR in subtropical regions (e.g., Sichuan Basin and Middle-lower Yangtze River Basin) showed a prominent increase. In line with our study, other NIR projection studies also anticipated the increased water consumption in subtropical regions (Ye et al., 2015; Zhu et al., 2015). However, as they assumed the fixed rice growth duration, the projected NIR in those studies was different from the results presents here. Thus, the vital effect of rice growth length on irrigation water requirement implies that phenology simulation is essential in investigating crop water consumption (Wriedt et al., 2009; Zhao et al., 2015).

4.2. Adaptation of China rice production to climate change

Warming shortens rice growth duration in northeastern China and increases heat stress in other regions (Figs. 4 and 5). Altering sowing date is considered as a useful strategy to slow down development rate and avoid heat damage (Zheng et al., 2012). In this study, under the optimized sowing date, rice yield was projected to increase (Fig. 5a). However, rice NIR would also increase dramatically under the optimized sowing date, especially for single-rice sites in northeastern China (Fig. 5c). This should be attributed to the following two reasons. First, rice growth duration was prolonged at most sites, which resulted in more time for rice to consume water by evapotranspiration. Second, shifted sowing date also reduced the synchronization of the rice key water consumption stage and precipitation period at most sites, leading to a large increase in NIR (see examples in Fig. 7). However, it should be noticed that shifting sowing date could only partly compensate the negative effects on rice yield in northeastern China. More adaptation strategies are thus necessary to employ. Fortunately, the response mechanism of rice yield to warming allows using new rice variety to adapt to climate change (Liu et al., 2012; Li et al., 2016; Zhang et al., 2017). For single rice in northeastern China and Yunnan-Guizhou plateau, although the earlier sowing date slowed down the development rate, rice growth duration would still be shorter (on average of 12 days) than that in the baseline period. Thus, given the negligible heat stress (Fig. 7a), longer maturity variety should be adopted. In line with our study, a recent study showed that in the past 30 years, rice growth duration in northeastern China has increased for more than 5 days with the rising temperature, meaning that famers have begun to use longer maturity variety in the practice to compensate the negative impacts of climate change on rice yield (Tao et al., 2013). For rice in other regions, using heat tolerant or shorter maturity variety is imperative, as the severe heat stress in booting and heading stages cannot be totally avoided by shifting sowing date (Fig. 7b and c).

4.3. Uncertainty and limitation

The projected impacts of heat stress on rice yield highly depend on the parameterization of rice spikelet fertility response to temperature. However, as limited by experiment data, our study and almost all previous studies (i.e., Shen et al., 2011; Wang et al., 2014, 2017a; Tao

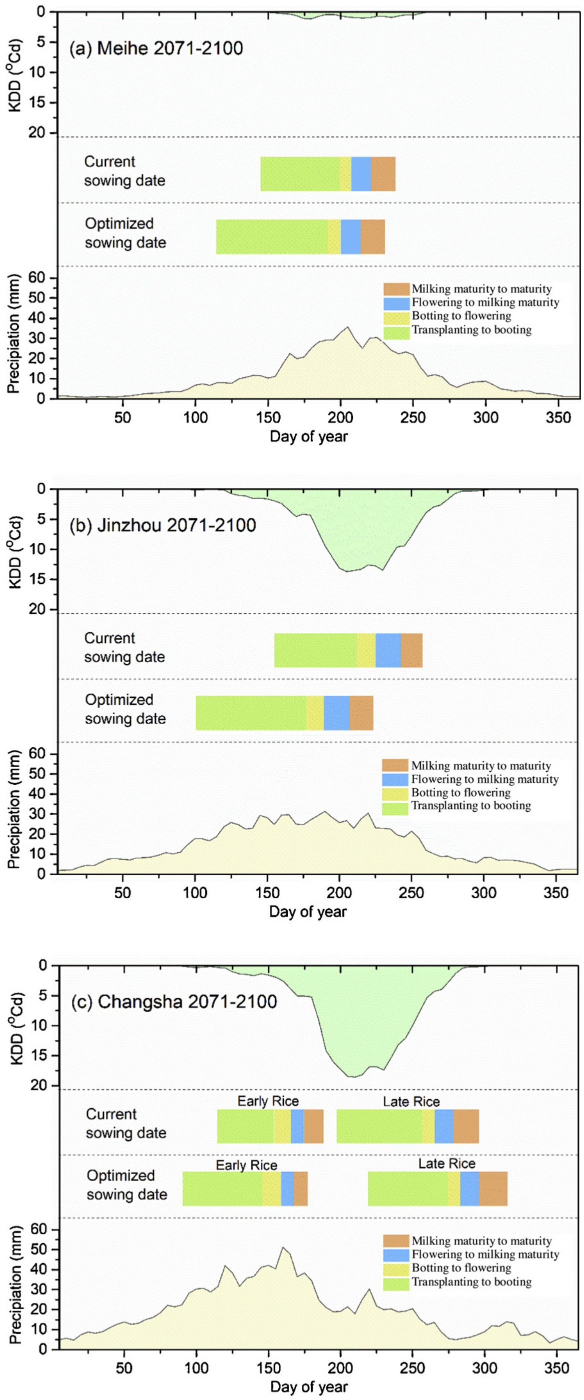

Fig. 7. Five days average precipitation (pale-yellow shadow) and KDD (pale-green shadow), as well as average rice growth process (colored rectangles) under current and optimized sowing dates during 2071–2100. Meihe (MH) is a single rice site located in in northeastern China with a temperate climate, Jinzhou (JZ) is also a single rice site located in the Middle-lower Yangtze River Basin with subtropical climate, while Changsha (CS) is a double rice site with subtropical climate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2008, 2013; Zhao et al., 2016) assumed that the heat tolerance parameter did not vary across the whole study regions and was set as default (Fig. 2). Thus, losses of rice yield from heat stress are almost certainly overestimated, which is especially true for single rice in subtropical regions, where some varieties have been found to have stronger heat resistance (Cao et al., 2008; Fu et al., 2012). Similarly, a statistical study showed that American maize yield in regions with higher temperature are less sensitive to heat stress (Butler and Huybers, 2013), indicating that famers have begun to adapt to heat damage in practice, but to what extent do crops adapt to the heat stress is still not clear, which is beyond the scope of this study. Thus, it is necessary to obtain more robust results of climate change impacts based on the accurate parameterization of rice spikelet fertility response to temperature in future study. However, only few previous experiments have focused on the heat resistance of different rice varieties. Although some studies have begun to test the response of the heat resistance of local rice varieties to high temperatures (e.g., Li et al., 2014; Cheabu et al., 2019; Wang et al., 2019), most of them only tested regional varieties. This suggests that more comprehensive temperature control experiments should be conducted to estimate the current heat resistance range of rice in China. Apart from the uncertainty of heat tolerance parameter, an experimental study suggested that rice development rate does not reduce as quickly at higher temperature as we expected previously (van Oort et al., 2011). This might underestimate the yield loss for all three types of rice in subtropical regions, as growth duration would not increase that much compared with our results. It also should be noticed that although ORYZA v3 is the most widely used rice model, the effects of CO_2 concentration on crop transpiration was not considered (Bouman et al., 2001). NIR would thus undoubtedly be overestimated, since rice leaf transpiration rate would be reduced under elevated CO_2 (Bunce, 2014). Environment-control experiments showed that the reduction of rice evaporation rate under high CO_2 concentration (640 ppm) varied largely among different varieties, ranging from 4 to 25 % (Lin et al., 1996). Although some crop models (i.e., CERES-Rice) have already taken the effects of CO_2 concentration on rice evaporation into consideration, these environment experiments are necessary to improve the model simulation of the variety-specific response of crop transpiration rate to elevated CO_2 concentration.

Several other limitations and uncertainties of our study are worth pointing out here. First, rice irrigation was simulated under the scenario of full irrigation. In reality, water-saving technologies (i.e., control irrigation, wetting-and-drying and continuous soil saturation) have been developed and applied to replace full irrigation (Tabbal et al., 2002). These technologies not only dramatically increased water productivity, but also reduced irrigation frequency (Belder et al., 2004). Thus, promoting water-saving irrigation patterns should be a feasible adaption strategy to meet the shortage of irrigation water resources. Second, the impacts of altering sowing date on crop the rotation system was ignored. In China, apart from northeastern plain, rice-wheat and rice-oilseed rape rotation system dominated agricultural production in single rice regions (Cheng et al., 2013; Bai et al., 2016). Altering rice sowing date may thus occupy the normal growth windows of wheat or oilseed rape, thereby going against the total output of the agricultural production system. Finally, this study only applied one crop model in the projection of rice yield and NIR, while the simulation results varied largely across models (Asseng et al., 2013; Wallach et al., 2018). Recently, several studies carried out by Agricultural Model Intercomparison and Improvement Project (AgMIP) have suggested that using model ensembles for simulating the impact of climate change on crop yields offers the opportunity to acquire more reliable results (Asseng et al., 2013; Bassu et al., 2014; Li et al., 2015). More robust multiple models' analysis through international collaborations should be conducted in the future.

5. Conclusion

Shifting sowing date is considered as a useful strategy in dealing with the impacts of climate change on Chinese paddy rice production. In this study, we explored if shifting sowing dates will compensate the reduction of rice yield during 2011–2100, and if more irrigation will be needed to meet the water requirement for rice growth. We found that under the effects of global warming and elevated consideration of CO_2

effects, future rice yield would continue to decrease while irrigation water requirement (NIR) would increase dramatically. Yield losses for rice in temperate regions (northeastern China and Yunan-Guizhou Plateau) were mainly caused by the sharply shortened growth duration, while the losses in the other regions were mostly derived from the substantial heat stress. To maximize rice yield, the sowing date of single and early rice at most sites should be earlier than the current dates. However, in regions with sever heat stress such as Yangtze River Basin, postponed sowing date was a more appropriate choice to avoid flowering period occurring in the extreme hot days. Apart from northeastern China, the suitable sowing date could improve rice yield dramatically and completely compensate the yield losses due to the severe heat events. Meanwhile, NIR would further increase under the optimized sowing date without exception. To better compensate the negative effects of climate change on rice yield and improve the utilization of precipitation, breeding longer season varieties in northeastern China and heat tolerant varieties in subtropical regions would be the best adaptation strategies. The results are of great importance not only for food security, but also for the sustainable utilization of water resources.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2019.105890.

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