

# Impact assessment of climate change, carbon dioxide fertilization and constant growing season on rice yields in China

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**Abstract** Rice is the staple food in China, and the country's enlarging population puts increasing pressure on its rice production as well as on that of the world. In this study, we estimate the impact of climate change, CO<sub>2</sub> fertilization, crop adaptation and the interactions of these three factors on the rice yields of China using model simulation with four hypothetical scenarios. According to the results of the model simulation, the rice yields without CO<sub>2</sub> fertilization are predicted to decrease by 3.3 % in the 2040s. Considering a constant rice-growing season (GS), the rice yields are predicted to increase by 3.2 %. When the effect of CO<sub>2</sub> fertilization is integrated into the Agro-C model, the expected rice yields increase by 20.9 %. When constant GS and CO<sub>2</sub> fertilization are both integrated into the model, the predicted rice yield increases by 28.6 %. In summary, the rice yields in China are predicted to decrease in the 2040s by 0.22 t/ha due to climate change, to increase by 0.44 t/ha due to a constant GS and to increase by 1.65 t/ha due to CO<sub>2</sub> fertilization. The benefits of crop adaptation would completely offset the negative impact of climate change. In the future, the most of the positive effects of climate change are expected to occur in northeastern and northwestern China, and the expansion of rice cultivation in northeastern China should further enhance the stability of rice production in China.

## 1 Introduction

Rice is the main food staple in China, and 18.5 % of the world's rice-growing area is located in this country. China contributed 28.0 % of the global production of rice in 2011 (FAOSTAT 2013), and this production strongly affects the world rice market (Slayton 2009). The total population of mainland China continues to increase from 1.34 billion in 2010 to a projected

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1.5 billion in 2030 (Peng 2011). In upcoming decades, it will be necessary to produce more rice to feed China's increasing population, and this will increase the pressure on rice production in China. There is therefore an increasing need to assess the effects of global changes on future rice yields.

Crop simulation models are important tools for impact assessment on various scales, including the site (Bannayan et al. 2013), national (Lin et al. 2005; Xiong et al. 2012), continental (Masutomi et al. 2009), and global (Deryng et al. 2011) levels. In particular, large-scale models that directly use the output from climate models have been developed due to a need to simulate the impact of climate variability and change on crops (Challinor et al. 2009).

Over the past three decades, the climatic conditions, the fertilization intensity and the rice varieties that are cultivated in the paddy fields of China have undergone significant changes. During the most recent period (the satellite era, 1979–2006), the temperature in China has risen by  $0.45 \pm 0.13$  °C per decade (Li et al. 2010). The consumption of nitrogen (N) as fertilizer in China increased from 9.4 Mt in 1980 to 23.8 Mt in 2011 (National Bureau of Statistics of China 2013). Genetic improvements, expressed as enhanced photosynthetic efficiency, have made important contributions to the impressive growth of rice yields (Mao 2010; Peng et al. 2000, 2008). Advances in technology and changing agronomic practices have also been responsible for significant increases in agricultural production in China (Yu et al. 2012a). However, the impact assessments of rice yield in China have been based on a lower yield level in recent decades (Lin et al. 2005; Xiong et al. 2009b). When such impact assessments are implemented, current rice yields that consider agricultural intensification and renewal varieties should be selected as the yield baseline.

In addition to the factors listed above, interactions between climate change and the growing season (GS) are poorly understood. In general, the length of the GS is controlled by the use of constant growing degree days (GDD) in most model simulations. Increased air temperatures will, therefore, shorten the length of the GS and result in yield losses (Ewert 2012). However, this hypothesis had been challenged by some other studies in China. They had found little or no change in the rice GS, and the adoption of new rice varieties stabilized the growing duration (Liu et al. 2010, 2012; Shrestha et al. 2013).

When an impact assessment of crop yields under climate change is implemented, the use of an updated yield baseline and the consideration of crop adaptation are valuable. The Agro-C model is a process-based model (Huang et al. 2009) that considers climate change, N fertilizer management and genetic improvements to assess the impacts of multiple factors on the rice yields in the last three decades (Yu et al. 2012a). In the present study, the Agro-C model was used to evaluate the impact of climate change, CO<sub>2</sub> fertilization and constant GS on the rice yields at the national scale in possible future climate change scenarios. The rice yields in China from 2000 to 2009 were used as the baseline for the impact assessment, and a constant GS (unchanged transplanting, heading and harvesting dates) was used to express crop adaptation. The model allows for the climate, CO<sub>2</sub> concentration and GS to be kept constant so that the relative contributions of various factors to the crop yields can be assessed (Gervois et al. 2008; Yu et al. 2012a).

## 2 Materials and methods

The rice paddy fields in China are distributed across temperate, subtropical, and tropical climate belts; the greatest rice production occurs in the subtropical belt. The total rice output comprises three types of rice. Double-crop early rice grows primarily in the provinces along

the Yangtze River and in the south. This rice is planted from February to April and is harvested in June and July. Double-crop late rice, which is planted after the early crop has been reaped, is harvested from October to November. Single rice grows in the southwest and the north; it is planted from March to June and is harvested from September to November. Based on the climate and cropping systems that are used, rice cultivation in China has been classified into 6 Agro-Ecological Zones (AEZs) and 15 subzones (China National Rice Research Institute 1988). These zones are summarized in Supplementary Table S1.

We used observed and predicted climate data from the PRECIS (Providing Regional Climates for Impacts Studies) system under two Special Reports on Emissions Scenarios (SRES, A2 and B2) to comprehensively consider the projected responses of the rice yields to climate change and elevated CO<sub>2</sub> levels in the next four decades. We input the observed and predicted climatic data, which were based on the measured data and future climate projections of PRECIS, into the Agro-C model. Using these data, we calculated the average change in production for each scenario considering the effects of climate change, CO<sub>2</sub> fertilization and constant GS. The simulation periods that were used were the 2000s and the four decades covering the period from 2011 to 2050; the 2000s served as the baseline period for the multifactor impact assessment.

## 2.1 Description of the Agro-C model

The Agro-C model is a biogeophysical model that consists of two submodels, Crop-C for simulating crop biomass and Soil-C for computing the soil organic carbon (Huang et al. 2009). The harvestable portion of the biomass, i.e., the yield, is calculated as the product of the biomass and the harvest index (Huang et al. 2007). Crop-C includes two main functional modules that are related to photosynthesis and autotrophic respiration. These modules use the environmental variables of temperature, solar radiation, soil moisture and atmospheric CO<sub>2</sub> concentration as input. The degree of crop N uptake depends on the common constraints of N availability and demand. The availability of N is determined by the mineralization of the soil N pool, synthetic N and manure N, which are assumed to follow first-order kinetics that are modified by the soil texture, temperature and moisture. The demand for N is determined by the crop type and the GS (Huang et al. 2009). The Agro-C model was used to simulate and predict the changes in the soil organic carbon stocks of China's croplands (Yu et al. 2012b, 2013) and to evaluate the relative contributions of cultivar improvement, climate and crop management in shaping the rice yields in China since 1980 (Yu et al. 2012a).

## 2.2 Climate data

The observed and predicted climate data were provided daily at a specific spatial resolution. The observed climate data for the 2000s, which included the daily mean, maximum and minimum temperatures, the precipitation, the wind speed, and the relative humidity, were obtained from the China Meteorological Administration. The datasets were obtained from 670 meteorological stations across China and are available online (<http://cdc.cma.gov.cn>). By applying an interpolation algorithm (Thornton et al. 1997) to these daily observations, raster layers (using a 10 km×10 km grid) of the meteorological data were constructed for each day. When the number of observations of solar radiation at the meteorological stations was not sufficient for the model, we adopted the method of Thornton et al. (2000) and used the rasterized daily precipitation and maximum and minimum temperatures to compute the daily solar radiation.

The present study used two SRES scenarios, A2 and B2, from 2011 to 2050. The A2 and B2 scenarios are also heterogeneous worlds, but A2 is regionally oriented economic

development, and B2 is local environmental sustainability (Nakicenovic et al. 2000). These scenarios were produced using the PRECIS system, a regional climate model that is driven by the initial and boundary conditions using the global climate model HadCM3. The PRECIS scenarios for China (50 km×50 km) were provided by the Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences (CAAS). The datasets for the PRECIS scenarios were previously used to assess the impact of climate change on Chinese agriculture (Lin et al. 2005; Wan et al. 2011; Yu et al. 2013). The temporal dynamics of the climatic factors from the two climate scenarios are presented in Supplementary Fig. S2.

The simulation that was conducted using Agro-C was based on the high-resolution grid (10 km×10 km), but the spatial resolution of the projected data was lower than that of the observed data. The PRECIS outputs were spatially downscaled for the high-resolution grid using the delta change method (Beldring et al. 2008; Hay et al. 2000; Prudhomme et al. 2002). This method is used to compute the differences between the current and future RCM simulations and to add these changes to the observed time series (Hay et al. 2000).

### 2.3 Simulation of the effects of changes in the rice yields

The changes in the future rice yields were simulated by applying the Agro-C model after up scaling it by rasterizing the model inputs using 10 km×10 km grid datasets for the parameters that included the climate, soils, crop management and rice varieties throughout China (Yu et al. 2012a). Each grid cell used a set of model inputs, and the model was applied in a cell-by-cell fashion covering the area of interest. We assigned a baseline scenario and four hypothetical management scenarios (shown in Table 1) to simulate changes in the rice yield and to evaluate the impact of multiple factors (climate change, constant GS and CO<sub>2</sub> fertilization).

The baseline scenario, S0, was computed using real datasets from the 2000s and was described in our previous study (Yu et al. 2012a). Historical datasets of the climate, crop management and variety renewal were used to compute the rice yields that were used as the baseline. S0 is a real scenario; the other scenarios are hypothetical scenarios that are designed to evaluate the impact of multiple factors on the rice yield. The simulation durations were one

**Table 1** Comparative characteristics of the baseline and hypothetical management scenarios

Scenario	Simulation duration	Fertilization management	Crop cultivar	Climate	CO <sub>2</sub>	Phenology
S0	2000–2009	Annual census data	Annual varieties parameters	Daily observed data	Annual observed CO <sub>2</sub> data	Constant GDD
S1	2011–2050	Constant average value of S0	Constant average value of S0	Projected scenario A2/B2	Constant average value of S0	Constant GDD
S2	2011–2050	Constant average value of S0	Constant average value of S0	Projected scenario A2/B2	Constant average value of S0	Constant GS
S3	2011–2050	Constant average value of S0	Constant average value of S0	Projected scenario A2/B2	Projected CO <sub>2</sub> concentration under A2/B2	Constant GDD
S4	2011–2050	Constant average value of S0	Constant average value of S0	Projected scenario A2/B2	Projected CO <sub>2</sub> concentration under A2/B2	Constant GS

decade for S0 and four decades for the other scenarios. For the four hypothetical scenarios, the fertilization management and rice varieties were maintained at the levels that were observed in the 2000s. Fertilization management includes the quantity of manure and N fertilization, and the rice varieties are distinguished by the photosynthetic capacity per unit canopy leaf nitrogen (Yu et al. 2012a).

Scenario S1 used the SRES A2 and B2 to reflect the independent effect of climate change on rice yields without considering CO<sub>2</sub> fertilization as a variable. In scenario S2, we defined crop adaptation as a constant GS that was derived from the Maps of the Agriculture Phenology in China (Zhang et al. 1987), which provided information regarding the crop phenologies, including the transplanting, heading and harvesting dates for the three rice types. In the Agro-C model simulation, the growing seasons for the three types of rice remained unchanged in the next four decades. Scenario S3, which integrated the projected CO<sub>2</sub> concentration under SRES A2 and B2 into the model simulation, represented the combined effects of climate change and CO<sub>2</sub> fertilization. In scenario S4, which represented the most optimal future scenario, three factors (climate change, CO<sub>2</sub> fertilization and constant GS) were used in the Agro-C model. In S0, S1 and S3, the constant GDD that controlled the rice phenology in the Agro-C model was calculated for each rice type. This constant GDD was also derived from the Maps of the Agriculture Phenology (Zhang et al. 2007). In this study, we focus mainly on the independent effects of climate change, CO<sub>2</sub> fertilization and constant GS. Therefore, the yield changes under the A2 and B2 climate projections were averaged after the simulation (Supplementary Fig. S4).

An additional input into the Agro-C model consisted of information regarding the soil properties. This information was derived from the spatial raster datasets of the Institute of Soil Science, Chinese Academy of Sciences. These datasets were constructed based on 10 km × 10 km grids and represented more than 7,000 soil profile measurements from throughout China. The majority of the soil profile measurements were conducted as part of the Second National Soil Survey of China and were completed in the early 1980s (Yu et al. 2007). The datasets provided the initial SOC density, total N content, soil texture and pH level for the topsoils (0–30 cm) of the croplands that were simulated in the model. Consistent soil datasets were used for all of the modeling scenarios.

### 2.4 Impact analysis

The impacts of the various hypothetical scenarios on rice yields were assessed quantitatively at the grid cell and regional scales. The  $\overline{\Delta Y}$  (average change in the yield) values for each hypothetical scenario for each rice type at the regional scale were calculated using the following equations:

$$PR_{Xs,sce,type} = \int_{\text{ForCurrent TypeRiceField}} Y_{Xs,sce,type} dA \tag{1}$$

$$\overline{\Delta Y}_{Xs,sce,type} = \frac{PR_{Xs,sce,type} - PR_{2000s,s0,type}}{PR_{2000s,s0,type}} \times 100 \tag{2}$$

where  $\overline{\Delta Y}_{Xs,sce,type}$  is the average change in yield (%) from the 2000s to the simulation period *Xs* in a given hypothetical scenario for a given rice type;  $PR_{Xs,sce,type}$  represents the average yield (t/ha) for the simulation period *Xs* in a given scenario for a given rice type (the yield is calculated using the integral area of  $Y_{Xs,sce,type,grid}$  over all of China [or six AEZs] for a given

type of rice field [single, early or late] because we did not consider land-use changes in this study);  $A$  is the area of cropland in a given rice type;  $Y_{Xs,sce,type}$  is the gridded 10-year average yield (t/ha) for the simulation period  $Xs$  in a given scenario for a given rice type;  $s_0$  represents the baseline scenario (S0 in Table 1); and  $sce$  represents the four hypothetical scenarios (S1, S2, S3 and S4 in Table 1). The subscript  $Xs$  corresponds to the simulation period (the 2000s, 2010s, 2020s, 2030s or 2040s).

### 3 Results

#### 3.1 Temporal changes in the yield

The annual rice yields of SRES A2 and B2 under the four hypothetical management scenarios (S1, S2, S3 and S4 shown in Table 1) were computed and are shown in Supplementary Fig. S3, which presents a dynamic view of the predicted changes in the rice yield in the next four decades. The baseline in the figure represents the decadal mathematical mean of rice yields in the S0 scenario. The average temporal changes in the yield for early, late and single rice under A2 and B2 are shown in Supplementary Fig. S4a–c, and the area-weighted rice yields based on the cultivated areas of the three types of rice in 2000 are shown in Supplementary Fig. S4d. In the S3 and S4 scenarios, which include CO<sub>2</sub> fertilization, the predicted rice yields show an increasing trend in the next four decades. In the S1 and S2 scenarios, which do not include the effects of CO<sub>2</sub> fertilization, the yields decrease compared to the baseline. The presence of a constant GS increases the rice yield in the scenarios with CO<sub>2</sub> fertilization (S3 and S4); the constant GS also offsets the decrease in the rice yield that was observed in the scenarios without CO<sub>2</sub> fertilization (S1 and S2). The temporal yield variability in Supplementary Fig. S4 would increase in the future, especially in S1 and S2, which did not include the effect of CO<sub>2</sub> fertilization. The minimum value of yield variability will appear in 2040s, and two adaptation measures (CO<sub>2</sub> fertilization and constant GS) are particularly useful for maintaining a stable yield.

Supplementary Fig. S5 shows the decadal changes and projected variations in the rice yields on a national scale. In S3 and S4, the predicted yields for all three types of rice increase over time. In S1, the changing trends of the early and single rice yields are reversed in the 2030s (shown in Supplementary Fig. S5a and c); for the late rice yield, the trend is reversed in the 2020s (shown in Supplementary Fig. S5b). The decadal variations (the error bar in Supplementary Fig. S5) in the early and single rice yields in the scenarios with constant GS (S2 and S4) are less than those that occur in the scenarios without constant GS (S1 and S3). However, for the late rice, the decadal variations under constant GS are greater than those under varying GS. In addition to the mean yields, the yield variability is very important for food production risk (Rosenzweig and Binswanger 1992). Chavas et al. (2009) discussed how the inter-annual climate variability impacted the crop yields in eastern China and found no increase in the inter-annual yield variability except for rice. In our simulation, the mean inter-annual yield variability from the 2010s to 2030s increased significantly and decreased slightly in the 2040s (Supplementary Fig. S5), and the overall spatial yield variability was 37 % for late rice, 22 % for single rice and 12 % for early rice.

We checked the predicted yield of area-weighted rice in the 2040s based on the cultivated areas of the three types of rice in 2010 (shown in Supplementary Fig. S5d); without CO<sub>2</sub> fertilization, the yield decreased by 3.3 % in S1. In S2, in which a constant GS was applied, the



yield increased by 3.2 %. In scenario S3, which integrated the effects of CO<sub>2</sub> fertilization, the yield increased by 20.9 %. In scenario S4, which integrated both constant GS and CO<sub>2</sub> fertilization, the yield increased by 28.6 %.

### 3.2 The spatial distribution of the yield changes in the 2040s

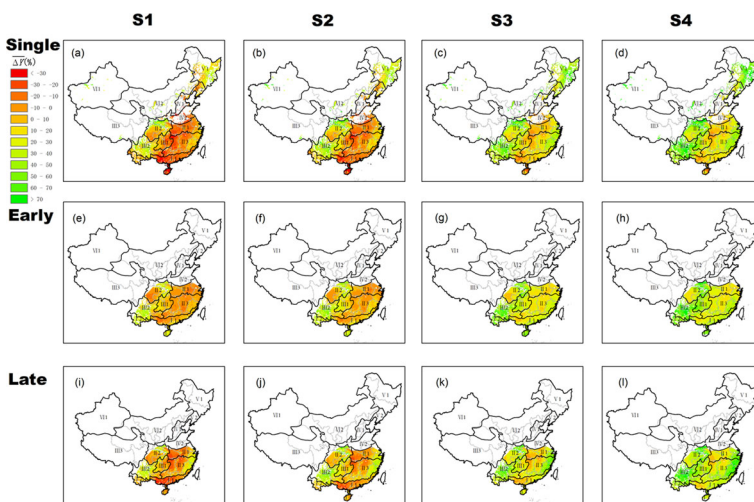
An examination of the predicted average changes in the yield ( $(Y_{2040s,sce,type} - Y_{2000s,s0,type}) / Y_{2000s,s0,type}$ ) without CO<sub>2</sub> fertilization in S1 revealed that climate change is expected to reduce the yields over a large area of China (Fig. 1). Whether the single rice or double rice yields were examined, the regions with decreasing rice yields were I1, III1, III3 and III1. The regions of significant potential increase were V1 for single rice and III2 for double rice.

Comparing the predicted average yield changes in scenario S1, the changes in scenario S3 are higher due to the effect of CO<sub>2</sub> fertilization. The combined impact of climate change and CO<sub>2</sub> fertilization is negative only in the tiny areas of southern China. When constant GS was considered in the simulation in scenario S4, the pattern of the rice yields was not significantly different from that which was observed in S3.

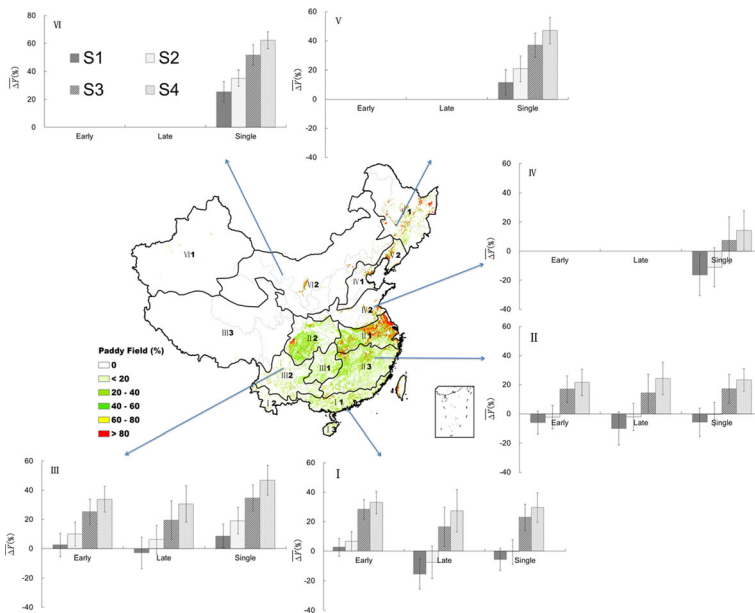
Figure 2 shows the predicted yield changes for various AEZs in the 2040s. In the scenarios with CO<sub>2</sub> fertilization (S3 and S4), both the single and the double rice demonstrated yield gains in China. In S1 (without CO<sub>2</sub> fertilization and with constant GDD), both the early and the late rice demonstrated yield losses in II; however, the early rice achieved yield gains, while the late rice achieved yield losses in I and III. In S1, the single rice showed yield gains in three regions (III, V and VI) and losses in another three regions (I, II and IV). In S2 (without CO<sub>2</sub> fertilization and with constant GS), the double rice demonstrated yield gains in III and yield losses in II, while the early rice achieved yield gains and the late rice achieved yield losses in I. In S2, the single rice showed yield gains in III, V and VI, yield losses in IV, and yield balance in I and III.

### 3.3 Constant GS and its impacts

Adaptation has been applied in an attempt to prevent decreases in the crop yield and to reduce the vulnerability of crop production (Challinor et al. 2009). In this study, we assigned a crop



**Fig. 1** Predicted average changes in the rice yield in the 2040s in four hypothetical scenarios



**Fig. 2** Predicted yield changes and variations in the 2040s in different scenarios. The error bars in the six charts represent the standard deviation of the predicted rice yield in a given scenario for a given decade

adaptation parameter to S2 and S4; this crop adaptation parameter was represented by constant GS in the model simulation in the next four decades. In contrast, in simulations S1 and S3, constant GDD was applied. The application of these parameters is consistent with the general treatment of crop phenology in many crop-simulation models (Lin et al. 2005; Xiong et al. 2009b; Yu et al. 2012a).

In the two climate scenarios A2 and B2, the average growth phase changes for the vegetative growth phase (VG, from transplanting to heading) and the reproductive growth phase (RG, from heading to harvesting) are shown in Supplementary Fig. S6. We compared the reductions in the growth duration in the constant GDD scenarios (S1 and S3) with those obtained in the constant GS scenarios (S2 and S4). With the exception of the RG for the late rice in the 2010s and 2020s, the growth duration was predicted to shorten in the next four decades. The most significant decreases were observed for the VG of the late rice and for the RG of the single rice.

### 3.4 The contributions of three factors in the 2040s

In this study, we used the Agro-C model to evaluate the predicted changes in the rice yields in four hypothetical scenarios, assuming that the sown acreage of rice and the distribution of paddy fields will remain the same in the next four decades as it was in 2010. The net impacts of climate change, constant GS and CO<sub>2</sub> fertilization between the 2000s and the 2040s are shown in Table 2. The net impact of climate change on the rice yields was calculated as the difference between S1 and S0, the impact of constant GS was calculated as the difference between S2 and S0, and the impact of CO<sub>2</sub> fertilization was calculated as the difference between S3 and S1. Climate change was predicted to have different effects on the various types of rice that were examined. The most sensitive rice type is late rice, whose yield is



**Table 2** Net effects of three factors on the rice yields between the 2000s and the 2040s

Type	Sown area (Million ha)	Baseline yield (t/ha)	Changes in yield (t/ha)		
			Climate	Phenology	CO <sub>2</sub>
Single	16.3	7.59	-0.10	0.50	1.82
Early	6.0	5.74	-0.15	0.24	1.36
Late	6.5	5.90	-0.61	0.47	1.51
Total	28.7	6.82	-0.22	0.44	1.65

predicted to decrease by 0.61 t/ha in the 2040s. The factor with the greatest positive effect on the rice yields was CO<sub>2</sub> fertilization, which was associated with a predicted increase of 1.82 t/ha in the single rice yield. The single rice exhibited the greatest sensitivity to changes under constant GS, with a predicted yield gain of 0.50 t/ha that was caused by constant GS offsetting reductions in the GS. For all of China, the yields of the area-weighted rice were predicted to decrease by 0.22 t/ha due to climate change, to increase by 0.44 t/ha due to constant GS and to increase by 1.65 t/ha due to CO<sub>2</sub> fertilization. Thus, constant GS is expected to completely offset the negative impact of climate change.

## 4 Discussion

### 4.1 The impact of climate change and CO<sub>2</sub> fertilization

Many factors that depend on the climate change conditions affect the rice yields, and interactions among these factors can strongly influence the reliability of the yield assessments (Challinor et al. 2009). Crop yields result from multiple nonlinear interactions between a series of processes, including climate change and CO<sub>2</sub> fertilization, which were examined in this study. Some research on the impact of climate change has suggested that the rising temperatures that are associated with climate change will have negative effects on future rice yields (Lin et al. 2005; Xiong et al. 2009a). However, these studies did not estimate the temporal changes that would occur due to the negative effect. In this study, we reached a similar conclusion regarding the impact of climate change in the 2040s (shown in Table 2). Our results show that scenario S1 does not always lead to a negative effect (only the climate change effect) during the period from the 2010s to 2040s. Using this scenario, a predicted trend reversal of the early and single rice occurs in the 2030s, and a reversal of the late rice occurs in the 2020s. Based on an analysis of the historic census yield and climatic data with statistical (Tao et al. 2008) and modeling methods (Yu et al. 2012a), there have been yield gains in northern China and yield losses in southern China. The results of this study suggest that the observed gain in northern China and the observed loss in southern China will continue in the next four decades (shown in Fig. 2). Some studies (Gammulla et al. 2010; Lanning et al. 2011) have proposed that excessive heat will result in serious damage to the crop yield, but it is difficult to quantify this damage in the process-based model. Completing the response function between extreme temperature and crop metabolism should be seriously considered in future studies.

In this study, CO<sub>2</sub> fertilization offset the negative impacts of climate change on all three types of rice (shown in Supplementary Fig. S5). However, relative studies have suggested that this offset may occur only during a certain period of time (Lin et al. 2005; Xiong et al. 2009a). In general, the response function of CO<sub>2</sub> fertilization in crop simulation models is

parameterized by enclosure studies. It has been argued that crop models overestimate the effects of CO<sub>2</sub> on plant growth and yield (Challinor et al. 2009; Long 2012). If the response function of CO<sub>2</sub> fertilization using the updated FACE experimental results (Ainsworth 2008) could be successfully parameterized in the new Agro-C models, the offset the negative impacts of climate change could be reassessed.

#### 4.2 Hot spots for rice yield changes in China

The fact that certain regions in southern China (I, II and III) are adapted to multiple cropping systems means that winter crop-single rice and winter crop-double rice may be conveniently interchanged when the limitations of thermal time accumulation are disrupted by increasing temperatures. According to the historical climate data and the demands of GDD for planting double rice, the northern limit for planting double rice has moved northward in the past three decades (Yang et al. 2011). Considering the increasing temperature in the SRES scenarios, this trend of northward movement is likely to continue in the next four decades. Comparing the results in southern China (I, II and III), our simulations show that planting single rice in region III is significantly more advantageous than planting double rice. There is no clear answer regarding which type of rice is more advantageous in regions I and II.

Only single rice is planted in northern China (regions IV, V and VI) due to the limitations of thermal time accumulation. Single rice grown in northern China achieved yield gains under all four of the hypothetical management scenarios that were tested, with the exception of region IV in S1 and S2. Considering CO<sub>2</sub> fertilization, the yield gains in V and VI were the highest (greater than 30 %) of all of the zones. The most positive effects of climate change were observed in northeastern and northwestern China (Fig. 2). While rice cultivation in the northwest is negligible, the proportion of sown areas in northeastern China increased from 2.3 % in 1980 to 18.5 % in 2010 (National Bureau of Statistics of China 2013). The expansion of rice cultivation in northeastern China would further enhance the stability of rice production in China.

An analysis of the climate and rice yields at the provincial level in the past three decades revealed that northeastern China is the only region in the country that has experienced a positive effect due to climate change (Tao et al. 2008). Similar studies have confirmed the positive effects of climate change on single rice cultivation in northeastern China (Chen et al. 2012; Zhou et al. 2013). Kim et al. (2013) used a calibrated and validated CERES-Rice model to simulate the rice yields under elevated CO<sub>2</sub> and various temperature conditions. These authors found that the projected yield increased as the latitude increased due to the reduced effects of temperature. The model that was used in our study explains the relative changes in the rice yields in different regions, as shown in Fig. 2. There is no doubt that the region with the greatest future potential for rice production is northeastern China, but water shortages are an undeniable reality in that area (Piao et al. 2010).

#### 4.3 Effects of crop adaptations

Many adaptation options (e.g., earlier planting dates and different crop choices) can be used to offset the impact of climate change. In this study, we modeled a simplified crop adaptation involving an unchanged rice GS in the next four decades. The quantitative indicator of this measure is shown in Supplementary Fig. S6. This measure would extend the GS, which is predicted to be shortened by increasing temperatures. The effects of the increasing yields exhibit a regional heterogeneity, which is shown in the chart in Fig. 2. The largest yield gaps between the scenarios with and without constant GS occurred for the late rice (Supplementary

Fig. S5b), for which increasing temperatures are expected to cause significant yield losses. Therefore, for the late rice, the most significant decreases of VG (Supplementary Fig. S6a) are consistent with the largest yield gaps between the scenarios with and without constant GS.

The yield increases that were observed in scenario S4 in this study only represent the potential crop adaptation and CO<sub>2</sub> fertilization due to the increasing temperatures and CO<sub>2</sub> concentrations. Other measures of adaptation, such as genetic improvements in photosynthetic efficiency and flexible planting dates, need to be quantified on various temporal and spatial scales in the future (Challinor et al. 2009). This new knowledge, as well as the modeling of novel crop adaptations, should be integrated into an updated model to improve the efficiency of crop simulation in future studies.

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