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Potential impacts of climate change and climate variability on China's rice yield and production

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ABSTRACT: We assessed the effect of greenhouse gas-induced climate change, as well as the direct fertilization effect of CO_2, on rice yields and production in China. Our methodology coupled the regional climate model PRECIS (Providing Regional Climates for Impacts Studies) with the CERES (Crop Environment Resources Synthesis) rice crop model to simulate current (1961–1990) and future (2011–2100) rice yields and production under A2 and B2 climate change scenarios. The movement of rice-producing areas to more favorable climatic conditions was also considered. Results demonstrate that simulated future rice yields decrease without the CO_2 fertilization effect and increase in some areas and time slices with it. Yield variability measured by the coefficient of variation exhibits increases in both scenarios, with the largest increases under A2. Due to favorable climatic conditions, single rice cropping may expand further north in China, and double rice cropping may move to the northern portion of the Yangtze River basin. China's potential rice production is projected to increase in the future, due to the CO_2 fertilization effect and shifts in rice-producing areas. Three rice cultivation regions (Sichuan basin, Yangtze River basin, and Huang-huaihai plain) are identified as highly sensitive to future climate change if no adaptation measures are implemented, due to yield decreases and large increases in production variability.

KEY WORDS: Climate change · PRECIS · Crop production · Rice · Variability · China

1. INTRODUCTION

The response of rice production to climate change is a major concern because of the crop's socio-economic importance within many rice-growing countries (Krishnan et al. 2007). Rice is an essential component of the diet in more than half the world's population, and it is the most socially and economically important crop in China, where, for example, in 2004, it comprised around 28.6 million ha of harvested area, producing 181 million tons of yield (FAO 2004). Although the rice cropping area represents only 29.1% of the total national crop growing area, rice production contributes 43.7% of total national grain production (Yao et al. 2007). Climate change is likely to cause alterations in the area of rice cultivated and the yield per unit area, which will potentially have significant impacts on the food supply in China.

Previous studies have assessed the impacts of climate change on rice yield (e.g. Matthews et al. 1997, Amien et al. 1999, Saseendran et al. 2000, Krishnan et al. 2007, Tao et al. 2008a), based on coarse resolution climate change scenarios from global climate models (GCMs) or scenarios assuming fixed increments of mean temperature or precipitation. Most of the simulations exhibited increased rice yield in China under various climate change scenarios, which was implicitly ascribed to an enhanced CO_2 fertilization effect, while the yield was projected to decrease without the consideration of the CO_2 effect. The positive effect of higher CO_2 on rice yields could be offset or negated if temperature were to increase above certain thresholds. Rice

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yields are likely to decline in the low-latitude regions, because crops in these areas are generally grown closer to their limits of temperature tolerance and, therefore, warming may subject them to higher stress. In mid- and high-latitude areas warming may benefit crops currently limited by low temperatures and short growing seasons.

The coarse resolution of GCMs and the scarcity of weather stations with long observation series (particularly in developing countries) have often limited modeling studies to a small number of selected stations and, consequentially, have hindered the representation of detailed regional findings within the overall presentation of climate change effects. Spatial patterns of climate change impacts on crop yield and available planting area at regional scales are important for understanding the vulnerability and adaptation of agricultural production to climate change (Tao et al. 2008b). These objectives could be fulfilled through employment of regional climate models (RCMs). Only a few studies have used RCMs to investigate the impacts of climate change on crop production (e.g. Yao et al. 2007), and they have only considered the effects of climatic change on yield, excluding the concomitant impacts of shifting production toward areas with more favorable climate. The objective of the present study is to evaluate the regional scale effects of climatic change and variability on rice yield and production across China, with emphasis on both yield change and changes in rice-producing area, so as to provide a comprehensive assessment of China's potential rice production under climate change scenarios.

2. DATA AND METHODS

2.1. Rice production in China

Rice cultivation in China is distributed across temperate, subtropical and tropical belts, with the greatest production in the subtropical belt. Of the total harvested rice area, >95% is irrigated (Maclean et al. 2002), mostly in the southeast, south and northeast of China. Small, scattered areas of rain-fed production occur in the north, northeast and northwest of China. Rice production has been divided into 6 major agroecological zones (AEZs I to VI; Fig. 1) by Zhu & Min (2001). These 6 zones have been further subdivided into a total of 16 sub-AEZs (e.g. I1 to I3), based on physical conditions, topography, soil geological formation, rainfall patterns, cropping systems and the development of irrigation. Over 95% of the rice area is located in South China (AEZ I), the Yangtze River val-

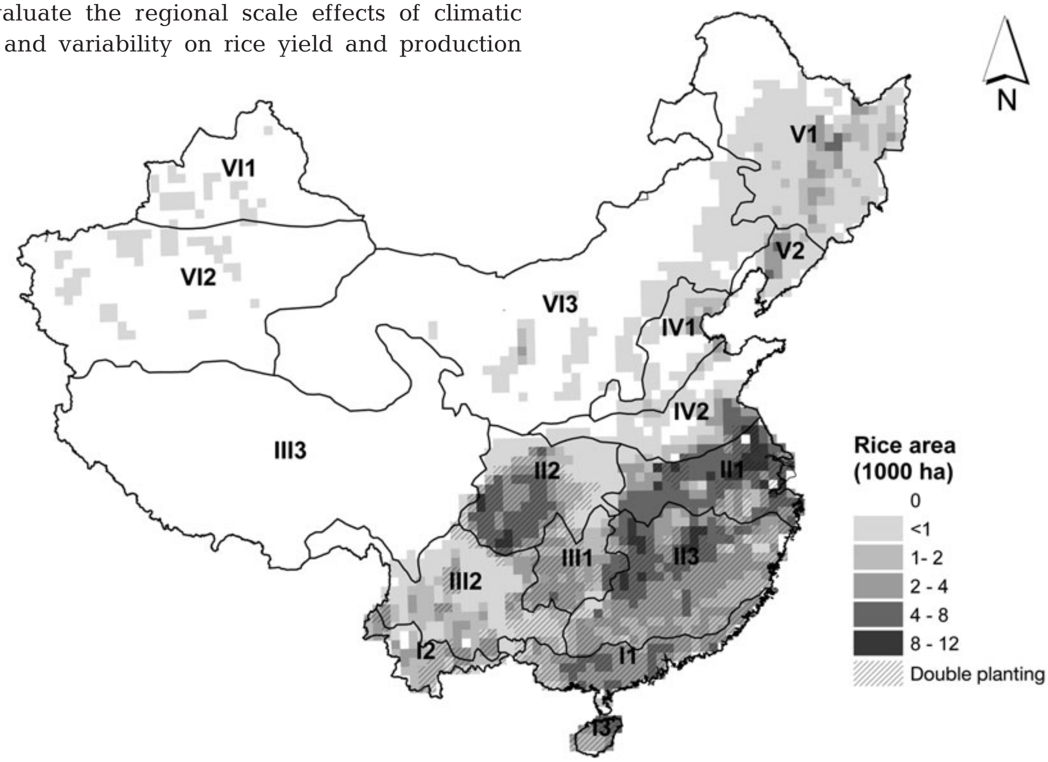

Fig. 1. Rice planting areas (2000) within the agro-ecological zones (AEZs) of mainland China and Hainan Island. Diagonal hatching indicates the areas with double rice planting. AEZs—I: South China, double rice cropping area; II: Central China, double and single rice cropping area; III: south-western plateau, single and double rice cropping area; IV: North China, single rice cropping area, V: NE China, early maturing rice cropping area; VI: NW China, single rice cropping area. For details, see Zhu & Min (2001)

ley and Sichuan basin (AEZs II and III) and NE China (AEZ V). The smallest area of rice cultivation is in NW China (AEZ VI), which only accounts for 0.5% of the total area. Most of the double-cropped rice is concentrated in sub-AEZs I1, I3, II1, II3 and III1, with small areas scattered in sub-AEZs I2 and III2.

2.2. High-resolution climate change scenarios for China

Using 2 IPCC (Intergovernmental Panel on Climate Change) SRES (Special Report on Emissions Scenarios) emission scenarios as drivers (A2 and B2), regional climate scenarios were generated for China by the high-resolution (~50 km grid interval) RCM PRECIS (Providing Regional Climates for Impacts Studies) (Jones et al. 2004). With the PRECIS-simulated daily weather for the period from 1961–1990 representing the present (baseline) climate, the future daily weather simulation was run for a 30 yr period from 2071–2100 and a technique called 'pattern scaling' (essentially a linear interpolation of changes over time; see Mitchell 2003) was used to generate results from 2011–2070. The average changes in temperature and precipitation for 3 future time slices (2020s: 2011–2040, 2050s: 2041–2070, and 2080s: 2071–2100) with respect to the baseline climate are presented in Table 1, along with the IPCC-prescribed changes in CO_2 concentration. The spatial patterns of temperature change show greater warming in the northern part of China (especially NE and NW China) relative to that in the south. This warming is more significant in winter than in summer (Xu et al. 2006). Increasing mean temperatures throughout China are accompanied by increases in climate variability and the length of the growing season (Zhang et al. 2006).

2.3. Crop model

We used the CERES-Rice crop model, which is embedded in the Decision Support System for Agrotechnology (DSSAT 4) Transfer software package (Jones et al. 2003). CERES-Rice is a physiologically based, management-oriented model that utilizes carbon, nitrogen, water and energy balance principles to simulate the processes that occur during the growth and development of rice plants within an agricultural system. CERES-Rice has been widely used to simulate the collective effects of plant genetics, management practices, weather and soil conditions on the growth, development and yield of rice plants (e.g. Singh & Padilla 1995, Mall & Aggarwal 2002, Mahmood et al. 2003). Temperatures between 14 and 32°C are considered in the model as optimal for photosynthesis. Outside this range, temperature has a negative effect on growth (Ritchie et al. 1998). Photosynthesis and evapotranspiration also respond to an increase in CO_2 by increasing stomatal resistance (Curry et al. 1990). The model requires input, including soil data (e.g. soil type, albedo, organic matter, texture, structure, bulk density), crop management data (e.g. sowing date, sowing depth, transplanting density, row spacing, irrigation, fertilizer) and various specific genetic coefficients. For the present study, the crop model was calibrated and validated for specific sites in the main rice-growing areas of China (Yao et al. 2007) and, at the regional scale, across all of China (Xiong et al. 2008). Model performance was adequate at specific sites, with simulated values being within ±10% of observed maturity duration and ±15% of observed yield. At the regional scale, the pattern of yield variation was well captured by the model and for most of the rice planting areas.

Table 1. Average changes (increases) in surface air temperature and precipitation (rainfall) under SRES (special report on emissions scenarios) A2 and B2 scenarios over China according to PRECIS simulation relative to baseline values (1961 to 1990), plus corresponding CO_2 concentrations

Periods	A2			B2		
	Temp. (°C)	Rain. (%)	CO_2 (ppm)	Temp. (°C)	Rain. (%)	CO_2 (ppm)
2020s (2011–2040)	1.4	3.3	440	0.9	3.7	429
2050s (2041–2070)	2.6	7.0	559	1.5	7.0	492
2080s (2071–2100)	3.9	12.9	721	2.0	10.2	561

2.4. Simulation runs and analysis for changes in yield and sown area

Using the CERES-Rice model, a baseline scenario was run for the period from 1961–1990, with observed values of CO_2 concentration in each year. The climate change scenarios were run for the period from 2011–2100 under annually increasing values of CO_2, as given by the IPCC SRES A2 and B2 scenarios. The simulation was run for all 50 × 50 km grids across China, with cultivar type and management parameters (such as sowing date, planting density) held constant within each sub-AEZ, based on data for 2000. Soil data, climate data and CO_2 concentrations were prepared for each grid, as described by Xiong et al. (2008). Each rice AEZ reflects aggregated values for cultivar type and management practices (details given in Xiong et al. 2008). Water and fertilizer were assumed to pose no stress on rice growth in the simulation. Rice is a C3 crop; therefore, the current understanding concerning its CO_2 sensitivity, based on the

IPCC FAR (Fourth Assessment Report) 2007 (Easterling et al. 2007) suggests that yields are moderately sensitive to CO_2. The present study uses a relationship of CO_2 concentration and photosynthesis based on the data of Kimball et al. (2002); an 850 ppm CO_2 concentration causes a roughly 40% increase in photosynthesis for rice, and different rice cultivars have the same CO_2 response function across China.

The output data extracted for yield change analysis are crop yield per unit area, expressed in kilograms per hectare. Mean rice yield changes for each grid were averaged for the study periods (see Section 2.2) under the 2 climate change scenarios. To calculate the changes in rice planting areas, a criterion described by Reyenga et al. (2001) was employed to identify suitable areas for rice planting. Holding the same geographical distribution of arable land as in 2000, a grid in which the annual probability of achieving a certain yield (4 t ha^{-1}) within a given 30 yr scenario is >0.5 was assumed to be a viable region for rice planting. In estimating the changes in rice planting area, the effects related to future water availability were not taken into account. Assuming no change in agrotechnology, China's national rice production was calculated from Eq. (1):

$$Y_{m,n} = \sum_{r=1}^{30}\sum_{i=1}^{q}\left((y_{m,n,r,i} \times A_i) + (y'_{m,n,r,i} \times A'_i)\right)\Big/30 \qquad (1)$$

where $Y_{m,n}$ is the averaged annual rice production under scenario m (A2 or B2), in period n, $y_{r,i}$ is the simulated yield of single rice or early sown rice in areas of double rice cropping system, and $y'_{r,i}$ is later sown rice in the double rice cropping system, for the rth year and ith grid (2622 grids in total were included). A and A' are the sown areas of single rice or early sown rice and later sown rice, respectively, for which baseline A and A' values were taken from Frolking et al. (2002) and Qiu et al. (2003), and were calculated for the future based on simulated yields and application of the yield criteria laid out by Reyenga et al. (2001). In addition, annual yields over 30 yr were compared between the baseline and 2080s values, in terms of the coefficient of variation (CV) and yield distribution at both national and regional scales, to analyze the effects of climate variability.

3. RESULTS

3.1. Impacts of climate change on rice production

3.1.1. Changes in rice yields

The national area-weighted rice yield changes for China compared to the baseline values (1961–1990) are listed in Table 2. Simulation results show that the meteorological variables of climate change (including changes in temperature, precipitation and radiation) decrease the rice yields in many of the time periods and scenarios, with the exception of the 2020s with scenario A2, with the yield decreases generally being greater under scenario B2 than under A2. The predicted yields increase if the CO_2 fertilization effect is included in the simulation; however, this effect can only offset the negative impacts of climate change in the short-term future. Yields would ultimately decrease long-term due to higher temperature under both A2 and B2, giving a national average yield change of –5.6 and –0.9% with A2 and B2, respectively, in the 2080s.

Without the inclusion of the CO_2 fertilization effect, rice yields generally decrease under scenario A2 across the whole of China, except in a few grids along the northern border of sub-AEZ III2. The decrease varies between approximately 60% in northwest, far northeast and central (sub-AEZs II1, II2, II3 and III1) China to 5% in the southwestern and southern parts of northern China. The results for scenario B2 show similar spatial patterns, but with a smaller range of yield change (data not shown). The spatial patterns of yield change with the consideration of CO_2 effects for the 2080s are shown in Fig. 2. Decreases in rice yields are also exhibited in a substantial number of grids, as in the cases without the CO_2 effect for both A2 and B2, but with smaller magnitudes. A2 shows a small to moderate increase in yields in south (I1, I3) and southwest (I2, III3) China and the west part of central China (II2) and in the southern part of NE China (V2), varying roughly from approximately 5% in I1 to 50% in NW China (Fig. 2a). For B2, average annual yield decreases are <15% for most areas, but with small increases (<15%) in III2, V2 and VI3 (Fig. 2b).

Table 2. Area-weighted (based on rice area in 2000) percentages of change in China's simulated future rice yields compared with yields during the baseline period (1961 to 1990), with and without CO_2 fertilization. The range (in brackets) represents regional changes, which include some very low baseline yields and hence very large percentages of change

Scenario	Change in average yield (%)					
	2020s		2050s		2080s	
	With	Without	With	Without	With	Without
A2	15.8 (–47 to 103)	6.3 (–51 to 88)	8.0 (–61 to 101)	–8.6 (–61 to 71)	–5.6 (–64 to 143)	–26.2 (–69 to 80)
B2	3.4 (–22 to 57)	–4.9 (–30 to 46)	0.02 (–48 to 77)	–12.6 (–45 to 56)	–0.9 (–52 to 82)	–18.4 (–55 to 52)

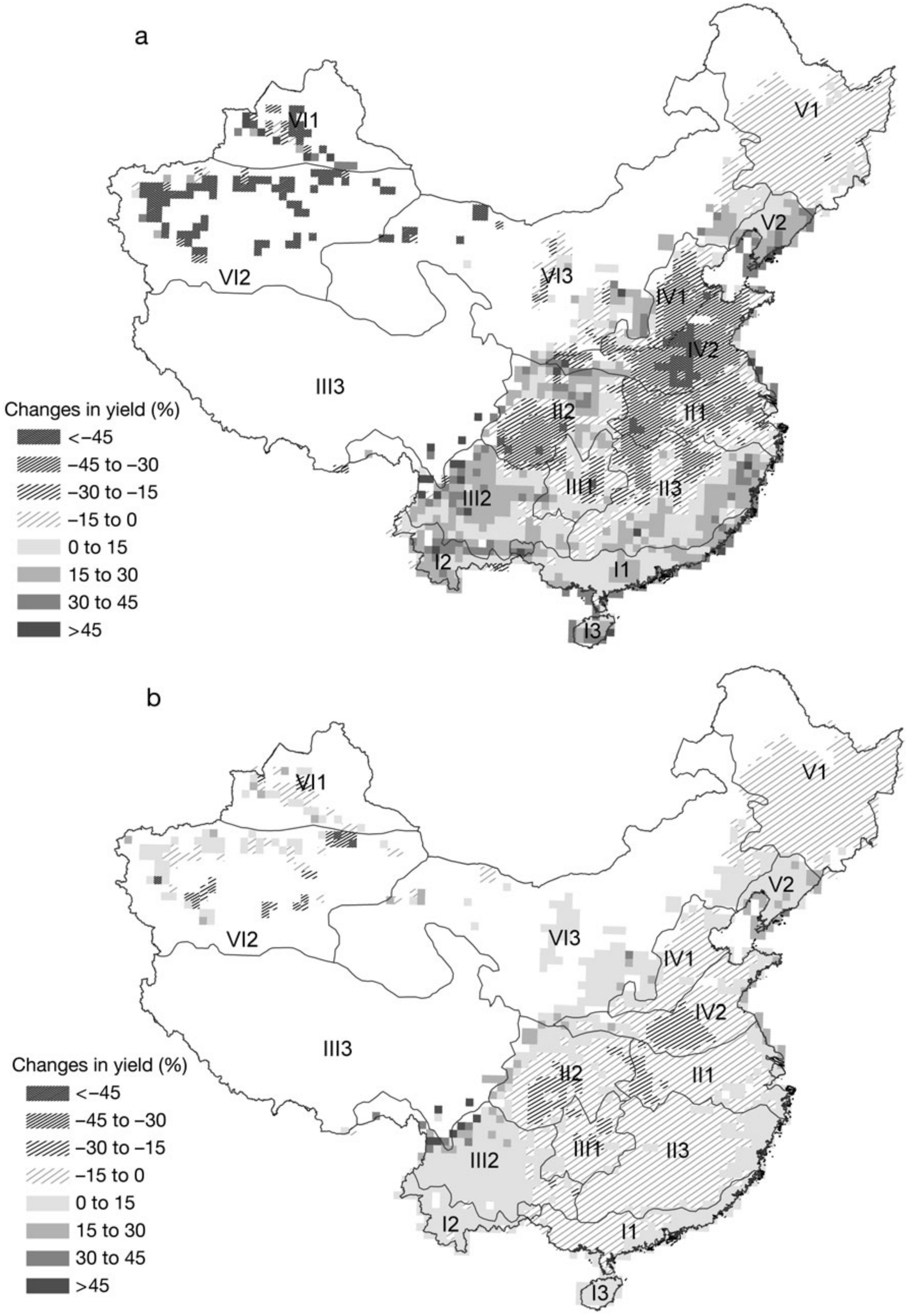

Fig. 2. Spatial patterns of yield change for paddy rice under (a) A2 and (b) B2 scenarios in the 2080s in mainland China and Hainan Island

3.1.2. Changes in rice planting area

Based on simulated year-to-year yields and the criterion for identifying suitable areas for rice planting, the changes in the cultivation areas for single and double rice planting were calculated for each time period. Fig. 3 shows the results for the 2080s with the A2 climate scenario. For single cropping, expansion occurs in the northern part of China (including sub-AEZs V1, V2, IV1, IV2, VI1, VI2 and VI3), which is consistent with the historical observations of changes in rice planting area from 1980 to 2000 (Tong et al. 2003). The largest increase is in V1. However, a few grids in sub-AEZs II2, III2, VI1 and VI2 show declining areas for single cropping due to less than economically acceptable median crop yields (4 t ha^{-1}) (e.g. sub-AEZs VI1 and VI2), or a more variable climate, which leads to a larger yield variability (e.g. II2 and III2). The potential increase of expanded areas for single-cropped rice is approximately 0.5 million ha in the 2080s with scenario A2.

For the double-cropping system, the increase is about 6.2 million ha in the 2080s with A2, if the present areas of single rice cropping can be completely converted into double rice planting when the climate becomes favorable. The areas with the climatic potential to expand to double rice planting are mainly located along the Yangtze River, e.g. II2, II2, III1, III2. However, areas suitable for double cropping decrease in some regions, e.g. III3, which are currently important rice production areas. Possible reasons are a shorter growth period and heat stress, particularly heat stress during the flowering period, which increases spikelet sterility and reduces the yield of later sown rice. Little difference exists between scenarios A2 and B2 in the area changes of rice planting.

3.1.3. Impacts of climate change on China's potential rice production

In the previous section we considered the changes in potential rice yields. In this section the changes are converted into estimates of potential production, by multiplying the simulated yield with the estimated areas of rice cultivation. These estimates are based on current (year 2000) observations of rice cultivated areas and a simple criterion incorporating future changes in crop suitability driven by changes in climate and CO_2 (see Section 2.4).

Fig. 4 shows the changes in national total rice production due to climate change. Without the effects of CO_2 fertilization, the losses in total rice production due to climate change are moderate to substantial when expressed as a percentage of baseline production, with changes of 9.7% (2020s), –1.5% (2050s) and –20.9% (2080s) with scenario A2 and –1.7% (2020s), –6.4% (2050s) and –12.8% (2080s) with scenario B2. The largest declines occur in AEZ IV (–43%) in the 2080s under the A2 climate and in AEZ II (–15%) under B2. Significant production increases are exhibited in some currently marginal areas of rice planting, with an approximately 30% production increase in AEZ V, and a doubling of production in AEZ VI. National production increases when the effect of CO_2 fertilization is included, with increases of 19.2% (2020s), 16.7% (2050s) and 2.7% (2080s) for A2, and 5.4% (2020s), 7.3% (2050s) and 6.4% (2080s) for B2. The greatest proportional increases in production are still from marginal areas, e.g. AEZs V and VI, although these are small when expressed as absolute gains. Small to moderate percentage increases occur in some of the main planting areas, e.g. AEZs II and III, which provide a major contribution to the total national production increase. However, whether with or without the effect of CO_2 fertilization, rice production variability increases in all cases in the future (increased standard deviation in Fig. 4), indicating enhanced future instability in national production.

3.2. Impacts of climate variability on rice production

Changes in variability and frequency/magnitude of extreme events that are likely to accompany climate change could pose a greater overall threat to crop production than changes in the average climatic conditions (Katz & Brown 1992). Fig. 4 shows that rice production is likely to become more variable in the future (as indicated by a larger standard deviation) in most time periods. To better quantify the influence of climate variability on rice yields, histograms of yields and their normal distribution curves for the three 30 yr periods (baseline and scenarios A2 and B2 estimates in the 2080s), based on the results from all grids, are shown in Fig. 5, with corresponding means, standard deviations and coefficients of variation.

Without the effect of CO_2 fertilization, climate change in the 2080s results in a yield distribution that is skewed toward relatively low yields under both A2 and B2 scenarios (Fig. 5a). The average decreases in mean yields between the baseline and future values, which represent the reductions in productivity due to climate change, are 1.62 t ha^{-1} (24%) with A2 and 1.42 t ha^{-1} (21%) with B2. Under consideration of CO_2 effects, the differences in mean yields between present and future values are

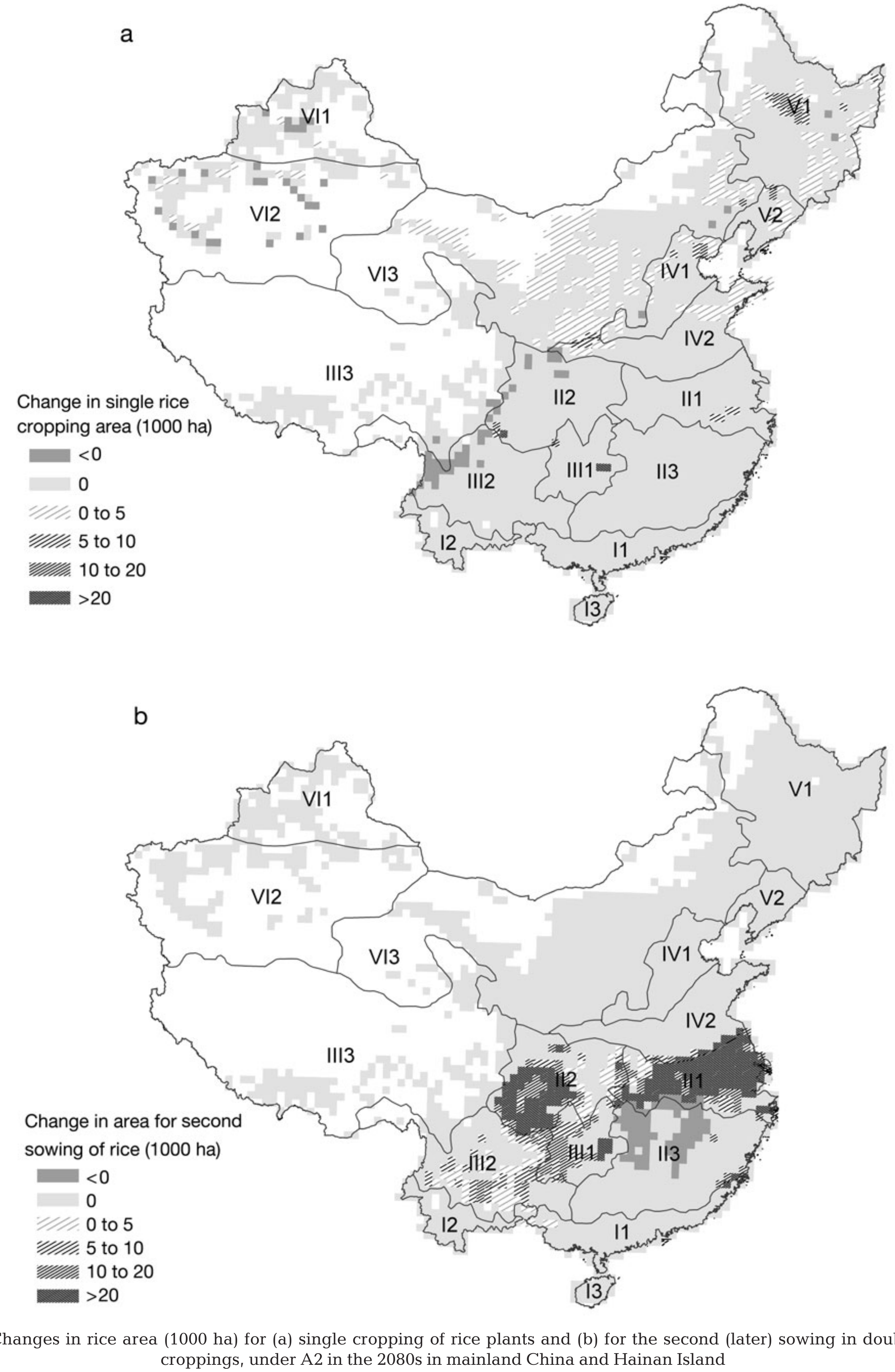

Fig. 3. Changes in rice area (1000 ha) for (a) single cropping of rice plants and (b) for the second (later) sowing in double rice croppings, under A2 in the 2080s in mainland China and Hainan Island

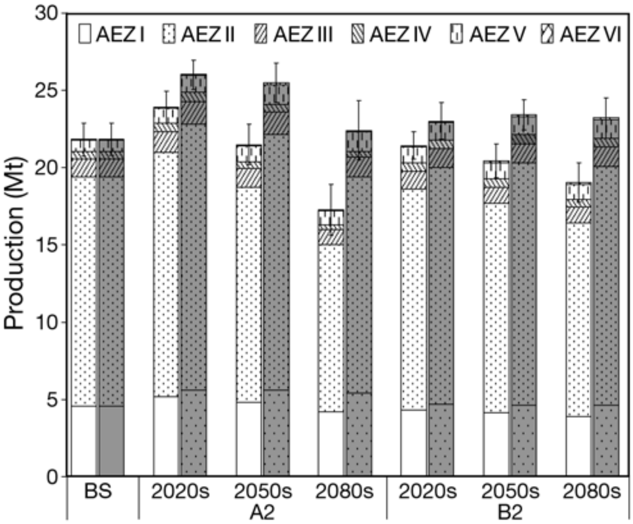

Fig. 4. Total paddy rice production for China under baseline (BS) and climate change (A2, B2) scenarios. White (grey) shading: without (with) the effect of CO_2 fertilization. Error bars: SD for total production values

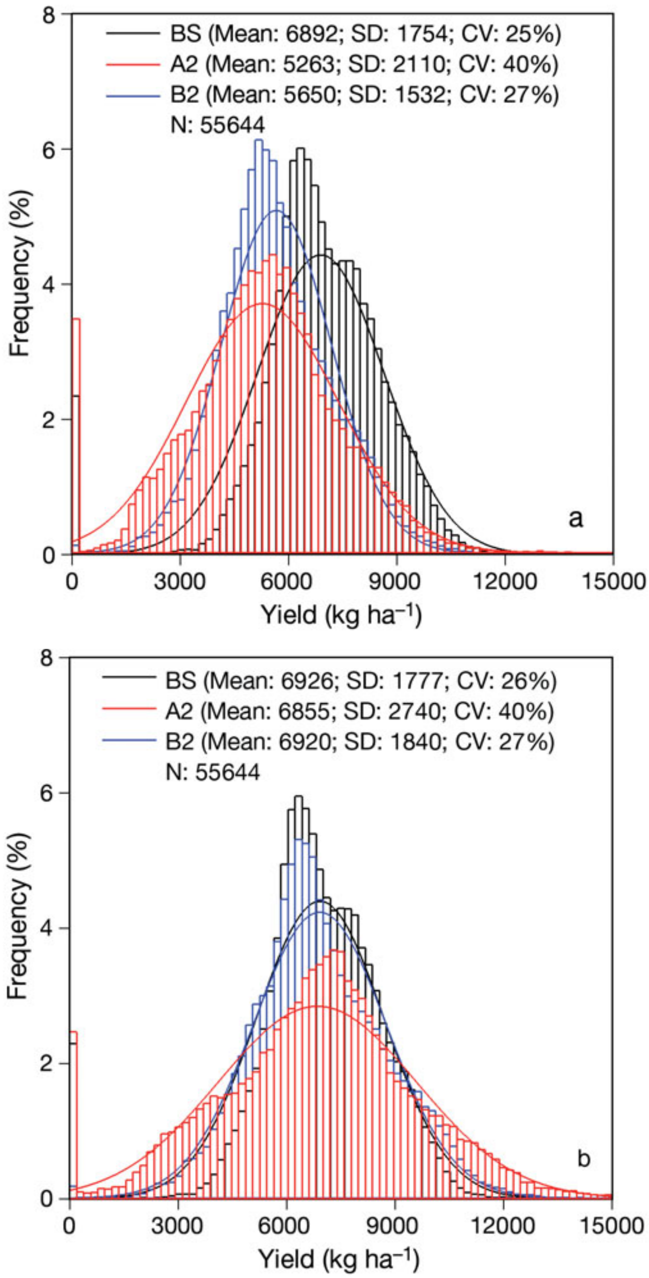

Fig. 5. Histograms of yield changes and their normal distribution curves with means, SDs and coefficients of variation (CV) for the baseline period (BS) and scenarios A2 and B2 in the 2080s (a) without and (b) with the CO_2 fertilization effect

generally small (Fig. 5b), indicating the limited depression of yields due to interactions of increasing temperatures and higher CO_2 concentrations. However, the yield distributions flatten and widen considerably, particularly with A2, revealing important aspects of the climate variability effect on rice yields. These patterns demonstrate that climate change has a different effect at different locations and in different years, and, consequently, increases the instability of national rice production and the imbalance among production areas.

The effects of climate variability on rice yields, measured in this case by the CV of annual yields, differ across regions. Fig. 6 shows the spatial patterns of changes in CV (with the CO_2 fertilization effect) for all of China. Similar patterns were observed for changes in CV between scenarios A2 and B2, while A2 shows a larger magnitude in changes. The CV more than doubles in some main rice-producing areas, e.g. the Yangtze River valley (sub-AEZ II1) and Sichuan basin (sub-AEZ II2), whilst it decreases by >60% in some grids in northeastern (AEZ V) and southwestern China (sub-AEZ III2). Most of the main rice-producing areas show increased production variability, particularly with the A2 scenario, e.g. sub-AEZs I1, II and III1, but a decreased CV is simulated in some peripheral areas, e.g. sub-AEZs I2, III2 and the southern part of sub-AEZ V1. The results demonstrate that increased spatial and temporal variability in rice production due to climate change will primarily occur in the main rice-producing areas, which implies enhanced instability of the rice production.

4. DISCUSSION

4.1. Yield change, CO_2 fertilization and climate variability impacts

Previous estimated changes in future rice yields and production in China had a wide range of values depending on the choice of crop model, GCM and sce-

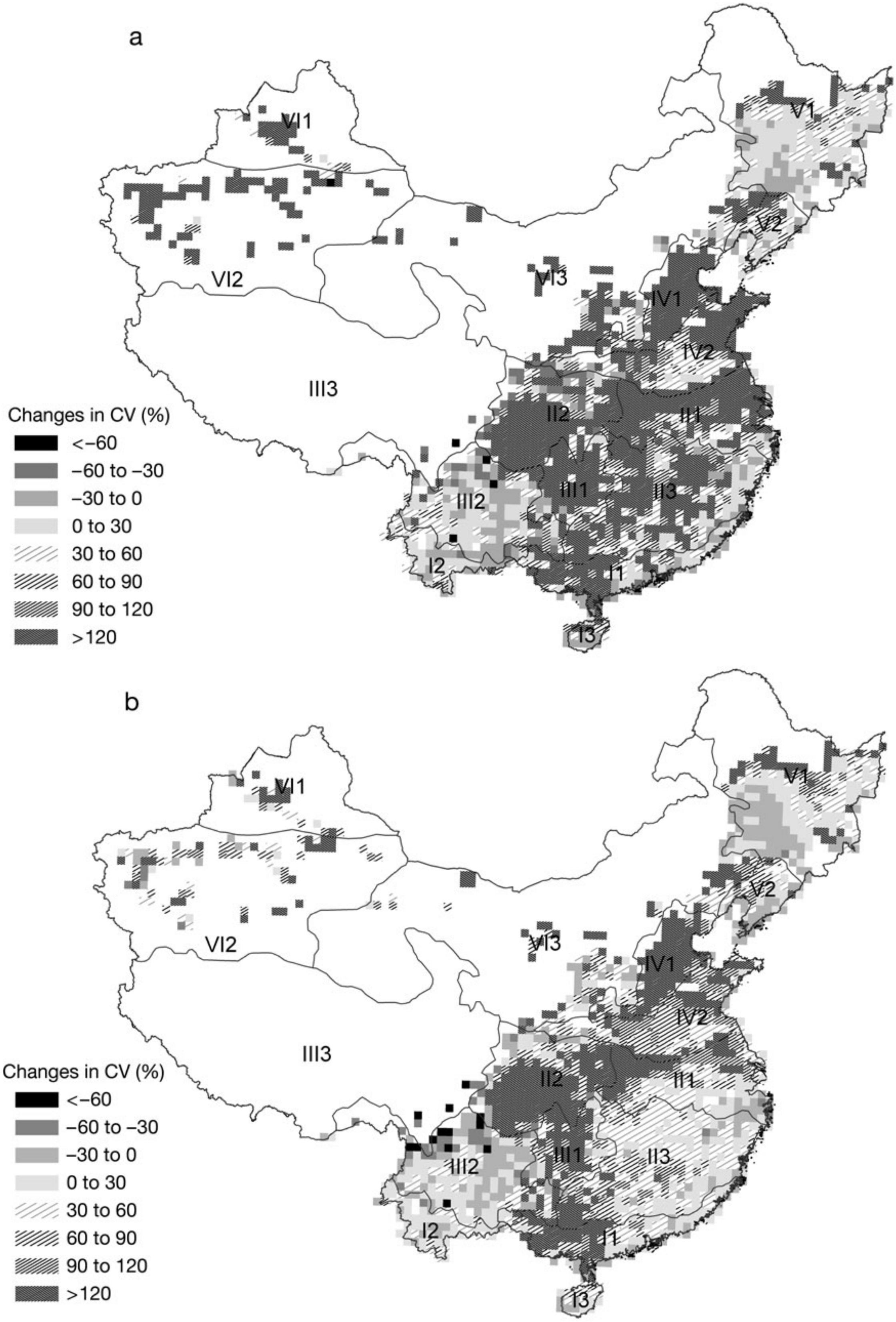

Fig. 6. Changes in the coefficient of variation (CV) of rice yields on a regional scale, in the 2080s with (a) A2 and (b) B2 scenarios in mainland China and Hainan Island

nario. For example, Matthews et al. (1997) predicted that doubled CO_2 climate change scenarios would lead to changes of –30.7 to 9.7%. Without the direct effect of CO_2 fertilization, Lin et al. (2005) documented changes of between –16.8 and –1.1% in average rice yield for the period 2011 to 2100. Yao et al. (2007) projected a decrease of 0.25 to 7% between 2071 and 2090. Our results show that climate change alone is likely to lead to lower rice productivity (with the exception of the A2 scenario in the 2020s), with changes in area-weighted yield of between 3.4 and –26.2% depending on the periods and scenarios. Approximate comparisons show that our results lie within the wider range of previous studies. The negative impact of climate change is striking in the 2080s, associated with the greatest increases in mean temperature, but relatively smaller in the 2020s and 2050s. These negative effects of climate change are mainly associated with the impact of higher temperatures on phenology, namely the acceleration of crop development (Porter 2005). Our simulations demonstrate that a significant shortening of the growing period for rice will occur in most grids under both A2 and B2 scenarios, particularly in the 2080s.

Most site-specific simulations indicate that a small increase in temperature without considering the CO_2 fertilization effect will produce declines in yield, but that the combined effects of increases in the levels of CO_2 and temperature will increase yields (e.g. Saseendran et al. 2000, Krishnan et al. 2007, Yao et al. 2007). Our results support these conclusions. The CO_2 fertilization effect mitigated the yield impact by up to 20%, resulting in increases of area-weighted yields in the 2020s (15.8% for scenario A2 and 3.4% for scenario B2) and 2050s (8.0% for A2 and 0.02% for B2) and small decreases in the 2080s (–5.6% for A2 and –0.9% for B2). The effects of CO_2 on rice yields are critical to the overall results, but they remain highly uncertain. The parameterization of the CO_2 effect in CERES was originally inferred from data reported by Kimball et al. (2002). Conclusions drawn from these data were recently questioned by Long et al. (2005, 2006) and reaffirmed by Ziska & Bunce (2007) and Tubiello et al. (2007). Recent re-analyses of FACE studies by the IPCC FAR 2007 have indicated that a 550 ppm atmospheric CO_2 concentration would cause a 10 to 25% increase of yield for C_3 crops under unstressed conditions (Easterling et al. 2007). Our simulations related to the offset in rice productivity by the CO_2 fertilization effect were 8 to 20% depending on climate change scenario, time period and CO_2 concentration; these results are reasonable and quantitatively consistent with the conclusions of IPCC FAR 2007.

It is important to take into account changes in climate variability when deriving regional climate scenarios for crop impact assessments, because for many stakeholders, for example grain traders, the year-to-year patterns of production are more important than the changes in mean yield due to climate change. Drought and heat have been ascribed as the primary climate stresses for yield losses in the major rice-growing areas of China (Peng et al. 2009). Since rice was irrigated in the simulation, impacts of climate variability other than temperature and radiation were not covered in the present study. Therefore, it should be noted that the impacts caused by climate variability are potentially underestimated. Projected climate change scenarios produced higher year-to-year variability in yields, as expressed by CVs, relative to that of the baseline period, but with higher values under scenario A2 and lower values under scenario B2. The increases in CVs in the future were attributed to the higher risk of spikelet sterility, due to more frequent heat stress events, which, in turn, led to substantially lower yields. High temperatures have recently been observed to cause great losses in rice yield in the Yangtze River valley (Fu et al. 2008). The projected weather data from PRECIS suggest that these yield loss-related higher temperatures (average temperature >30°C and maximum temperature >38°C during the reproductive period) will increase significantly in the future. The direct CO_2 effect had no influence on simulated yield variability; the CVs were similar in simulations with and without consideration of the CO_2 effect.

4.2. Yield changes by region and changes in planting area

Climate change is expected to have uneven impacts on rice production in different regions. Without the CO_2 fertilization effect, rice yields decrease universally across China for all 3 time periods, with substantial decreases in central China (sub-AEZs II1, II2 and III1), moderate decreases in NE China (sub-AEZs V1 and V2), and less pronounced decreases in South China (sub-AEZs I1 and I3) and SW China (sub-AEZs I2 and III2). When the CO_2 effect is included, increases in simulated yields are exhibited in most areas for the 2020s and 2080s. For the 2080s, small to moderate yield increases occur in south (sub-AEZs I1 and I3) and SW China (sub-AEZs I2 and III2) and portions of NE China (sub-AEZ V2), with decreases in other regions. The CO_2 effect led to a reduced area with yield decreases and to lower yield decreases.

Three regions are identified as being vulnerable to climate change impacts in terms of decreasing yields (Fig. 2) and increasing CV (Fig. 6), particularly with scenario A2 and in the 2080s: (1) the Sichuan basin and its peripheral areas, including sub-AEZs II2 and III1;

(2) the Yangtze River valley, consisting of sub-AEZ II1 and the northern part of sub-AEZ II3; and (3) the Huang-huaihai plain, including sub-AEZs IV1 and IV2. The Sichuan basin and Yangtze River valley are the 2 main rice-producing areas in China, so that decreases in yields in these areas will have great implications for future food security in China. Possible reasons for the simulated yield decreases in these areas are more frequent crop failures and yield losses due to increased heat stress in the future. Recently, warming has caused greater yield losses due to more frequent high temperature events, which resulted in notable losses in the Yangtze River basin (Fu et al. 2008). An increase in heat events in the future will induce greater losses in yields and higher variability in production if heat-resistant cultivars cannot be adopted. In some other regions, e.g. NE China (AEZ V) and South China (AEZ I), simulated yields exhibit either less pronounced decreases or slight increases in the future, with smaller increases or decreases in the CV. NE China might benefit from climate change, due to the currently low temperature (Yang et al. 2007). For South China, the present heat-resistant hybrid cultivars and reasonable sowing dates appear to be effective buffers under the climate change scenarios.

Climate change will not only affect rice production through direct effects on yields, but it will also affect where cultivation is possible/optimal. Although the total area planted with rice declined from 1981 to 2000, due to, inter alia, urbanization and changes in land-use policies, the areas planted for rice in some northern provinces actually increased. For example, Heilongjiang province (in the far northeast) has almost tripled its rice area from 210 000 ha in 1980 to 835 100 ha in 1995. The proportion of total area of rice cultivation in northern China (including northeast, northwest, north and plateau regions) increased from 4.3 to 7.5% between 1980 and 1995 (Tong et al. 2003). Higher temperatures associated with recent warming trends are generally held to be an important reason for this increase, according to discussions with agricultural enterprise agents in Heilongjiang provinces. The incorporation of shifts in the rice-producing area in our simulation contributed a 3 to 8% increase in the simulated national rice production, depending on the climate change scenario and future period. This shift included the expansion of the single rice cropping system into some areas of northern, northeastern and northwestern China, and the conversion of early rice/winter wheat or maize cropping systems to the double rice (early rice and later rice) cropping system in the northern part of the Yangtze River basin. However, the criterion adopted for identifying the changes in rice-producing area does not take all the determinant aspects into account. Besides favorable climate, abundant water is also a key factor for rice planting. Since we assumed that water is not limited in the absence of available agricultural water supply information, our results might produce an overestimation of the likelihood of changes to the distribution of rice cropping systems.

4.3. Limitations of the study

Like most studies on climate change effects on agriculture using crop models, this study suffers from several potential uncertainties and limitations. The major uncertainties are the use of a single RCM to generate the climate change scenarios. Different climate models would produce disparate spatial and temporal patterns of regional climate change even if they projected the same mean change of temperature or precipitation. Therefore, an approach that uses several climate models to assess impacts would reduce uncertainty in future work. Crop models, such as the one used in the present study, do not account for all of the important environmental and management factors affecting plant development and growth. The impacts of tillage and catastrophic weather events, like storms, heavy rain, hail, are not accounted for, and the quality of the simulations may be inadequate under conditions of severe environmental stress. The same is true for pests, competitors and diseases, which are not considered in the CERES-Rice models. In order to facilitate the simulations and to focus solely on the impacts of climate change, we assumed, for instance, that irrigation water is not limited and that pests (insect, diseases, weeds) pose no limitation to crop growth and yield under both current and future climate scenarios. These ideal conditions are likely to underestimate negative effects, or overestimate the positive impacts of climate change on rice production.

Compared with previous research in China, the main improvement here is the employment of regional simulation, which enables policy makers to understand the patterns of yield change in more detail. This facilitates the development of macro-strategies in terms of adaptation, such as the adjustment of planting structures, or the construction of commodity grain-producing areas. In addition, the present study allows us to estimate the impacts of climate change at a national scale, providing a quantitative way to measure the food supply under a series of scenarios (including e.g. climate change, socio-economics, policy). Furthermore, this simulation method provides the possibility of incorporating the results of other regional simulations (e.g. hydrological simulation, land-use change simulation, etc), in order to assess the integrated impacts of climate change on food production.

5. CONCLUSIONS

The present study identifies 3 impacts that may be important in determining China's potential rice production under 2 climate change scenarios: changes in mean yields, production areas and yield variability. Simulated rice yields decrease without inclusion of CO_2 fertilization, but generally increase when the CO_2 effect is incorporated. Yield variability is projected to increase both with and without direct CO_2 effects. Climate change induces shifts in rice-producing areas, with an expansion of single rice cropping in the northern part of China and the conversion of the single rice cropping system to the double rice cropping system along the Yangtze River. The national mean rice production is estimated to increase by 2.7 to 19.2% considering the combined effects of climate change, CO_2 and shifting rice-producing areas. Three rice production regions are identified as being susceptible areas to climate change impacts on yield and yield variability, they are the Sichuan basin, Yangtze River basin and Huang-huaihai plain. The 2 climate change scenarios are consistent regarding the direction of impacts, but with different magnitudes in the simulated change.

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