Using ORYZA2000 to model cold rice yield response to climate change in the Heilongjiang province, China

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\textbf{A B S T R A C T}

Rice (Oryza sativa L.) is one of the most important staple crops in China. Increasing atmospheric greenhouse gas concentrations and associated climate change may greatly affect rice production. We assessed the potential impacts of climate change on cold rice production in the Heilongjiang province, one of China’s most important rice production regions. Data for a baseline period (1961–1990) and the period 2010–2050 in A2 and B2 scenarios were used as input to drive the rice model ORYZA2000 with and without accounting for the effects of increasing atmospheric CO\textsubscript{2} concentration. The results indicate that mean, maximum, and minimum temperature during the rice growing season, in the future period considered, would increase by 1.8 °C under the A2 scenario and by 2.2 °C under the B2 scenario compared with those in the baseline. The rate of change in average maximum and minimum temperatures would increase by 0.6 °C per 10-year period under the A2 scenario and by 0.4 °C per 10-year period under the B2 scenario. Precipitation would increase slightly in the rice growing season over the next 40 years. The rice growing season would be shortened and the yield would increase in most areas in the Heilongjiang province. Without accounting for CO\textsubscript{2} effect, the rice growing season in the period 2010–2050 would be shortened by 4.7 and 5.8 days, and rice yields would increase by 11.9% and 7.9%, under the A2 and B2 scenarios, respectively. Areas with simulated rice yield increases greater than 30.0% were in the Xiaoxing’an Mountain region. The simulation indicated a decrease in yield of less than 15% in the southwestern Songnen Plain. The rate of change in simulated rice yield was 5.0% and 2.5% per 10 years under the A2 and B2 scenarios, respectively. When CO\textsubscript{2} effect was accounted for, rice yield increased by 44.5% and 31.3% under the A2 and B2 scenarios, respectively. The areas of increasing yield were sharply expanded. The area of decreasing yield in the western region of Songnen Plains disappeared when increasing CO\textsubscript{2} concentration was considered. The stability of rice yield would increase from 2010 to 2050. Overall, the simulation indicates that rice production will be affected positively by climate change in the next 40 years in the Heilongjiang province, China.

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1. Introduction

Rice is one of the most important crops in China, accounting for 18% of China’s total crop production area. The cold rice area in China refers to the region north of latitude 43°N, which includes all of the Heilongjiang province and the northernmost part of Jilin province [1]. In recent years, the Heilongjiang province has become the third largest rice-producing region in China, with 2.6 million hectares planted in 2009 [2,3]. The province’s abundant water resources, in combination with climate warming, are very likely to result in further expansion of rice production acreage in the province. However, as rice growth is sensitive to weather fluctuations, better understanding of rice response to temperature would be beneficial to this region’s agricultural industry.

Over the past 50 years the average increase in global surface warming has been 0.13 °C per decade, with the last 12 years (1995–2006) being the warmest [4]. In China, mean annual surface air temperature has increased by approximately 1.1 °C over the last 50 years, with almost 60% of this warming occurring in the most recent 16 years [5]. In northeast China, daily mean, maximum, and minimum temperatures during the growing season (May–Sept.) have increased on average by 0.34 °C, 0.28 °C, and 0.43 °C, respectively, in each decade, with no appreciable change in precipitation in the 1970–2009 periods [6]. Several studies have shown that the increasing temperature has affected rice production in several regions of China [7–9]. It is accordingly imperative that assessment of the effects of climate change on rice production be at the forefront of modern agricultural research in China.

In recent years, crop simulation models based on general circulation models (GCMs) have included future climate change scenarios as important components of research investigating the impacts of climate change. For example, Jin and Zhu [10] systematically evaluated the response of rice, wheat, soybean, and corn to atmospheric CO₂ concentrations using GCM data and crop growth models. Ge et al. [11] focused on the effects of climate change at each stage of rice growth in southern China and suggested measures for better adaptation to climate change. However, caution should be practiced when climate data obtained from GCM are used, as it has low spatial and temporal resolution, weakening its predictive ability in certain areas. Jones et al. [12] demonstrated the usefulness of using a downscaling method for regional climate scenario data acquisition with high temporal resolution. The regional climate model RegCM3 has been used to drive the EPIC model for analyzing potential impacts of climate change on the agricultural production in eastern China for the years 2071 to 2100 [13]. This analysis suggested that crop production would decrease by 2.5–12.0% if increase in atmospheric CO₂ was not accounted for, whereas productivity would increase by 6.5–24.9% if rising CO₂ was factored into the model. Shen et al. [14] evaluated the effects of increased temperature and atmospheric CO₂ on rice yields over the middle and lower reaches of the Yangtze River using the ORYZA2000 rice growth model based on the output of the PRECIS regional climate model under the Intergovernmental Panel on Climate Change (IPCC) SRES A2 and B2 scenarios. The results confirmed that CO₂ fertilization effects would markedly improve yields of various crops, but still would not offset the negative effect of climate warming, as also reported by Lin et al. [15], Yao et al. [16], and Xiong et al. [17].

As much of the reported work refers to the lower reaches of the Yangtze River and southern regions of China, the predicted effects of future climate change apply only to these warmer regions. It is desirable to investigate whether similar effects could appear in the colder northeast regions and how cold rice yield responds to climate change. The objective of this study was to investigate the effects of climate change on cold rice yield. Specifically, this study aimed to assess the combined effects of climate warming with CO₂ fertilization on cold rice production in Heilongjiang.

2. Materials and methods

2.1. Study sites

Twenty-five sites in the Heilongjiang province between latitudes 44–50°N and longitudes 123–132°E were selected to represent the cold rice region for this study (Fig. 1). These sites covered the whole province except for the northern region of Heihe, where rice is not grown.

To facilitate the analysis, we adopted the following four production regions as used by Wang et al. [18]: I) most suitable planting area including the middle of Sanjiang Plain and most of Mudanjiang; II) suitable planting area including the northeast part of Songnen Plain and some parts of Sanjiang Plain; III) somewhat suitable planting area with occasional water shortage including the southwest part of the Heilongjiang province; and IV) possible planting area including Xiaoxing’an Mountain and the Heihe region.

The climate in this region is classified as temperate continental monsoon [18]. The average annual temperature ranged from −5 to 5 °C in 1961–1990. The lowest average temperature was −23 °C and the highest was 20 °C. The region has a 100–150-day annual frost-free period. The annual cumulative temperature ≥10 °C is 2100 °C day. Daylight hours are 2400–2800 h per year, of which 44–48% occurs in the rice growing season (from May to September). The region’s average annual total precipitation is 300–650 mm, of which 83–94% falls in the rice growing season. The cropping system involves only one crop (rice) per year, with a 130–150-day season [19]. The soil is primarily paddy soil, with higher organic matter (e.g. 11.8 g kg⁻¹ < soil organic carbon < 128.9 g kg⁻¹) than soils of other areas in China [20].

2.2. Climate scenarios and meteorological data

The daily outputs of the PRECIS regional climate mode [12] under the A2 and B2 SRES emission scenarios were used in this study. Xiong et al. [21] showed that PRECIS has finer spatial (typically 50 km) and temporal (as daily climate data) resolution with spatial details (topography) and simulations of extreme climate events. The A2 scenario represents a medium-high emission scenario and is characterized by very rapid economic and population growth, while the B2 scenario represents medium-to-low emissions and emphasizes sustainable development. The periods 1961–1990 and 2010–2050 were selected to represent the baseline and future climate, respectively [12,22].
Meteorological data (2007–2010) were obtained from Jiansanjiang meteorological station in the Heilongjiang province and included daily maximum and minimum temperature, daylight hours, precipitation, average relative humidity, and mean wind speed. All variables were used in the calibration and validation of the ORYZA2000 model.

2.3. Experimental data

Field experiments were conducted at Jiansanjiang farm (47°14′N, 132°38′E) in the Heilongjiang province from 2007 to 2010. Experiments were designed as a four factorial split-split-plot design with sowing date as the main factor (early, medium and late) and cultivar (Kongyu 131, Longjing 21), nitrogen fertilizer rate (0, 105, 150 kg ha\(^{-1}\)), and irrigation method (conventional, slight dry–wet, highly dry–wet) as split factors. This study used experimental measured data from the treatments of the early-sown (April 15), variety Kongyu 131, conventional nitrogen application (105 kg ha\(^{-1}\)), and conventional irrigation (75 mm deep at each event). Nitrogen fertilizer was applied four times: at the transplanting (30%), tillering (30%), jointing (30%), and booting (10%) stages. Planting density was 112 plants m\(^{-2}\). There were 4 replications.

Main phenological stages were recorded for each plot. Leaf area index (LAI) and aboveground biomass (for green and dead leaves, stems and heads) were measured five to seven times during the growing season. Grain yield and grain weight were measured and grains per plant was counted at harvest. Grain dry weight was recorded 5, 10, 15, 20, 25, and 30 days following initiation of grain-filling to determine size development rate. LAI was estimated by multiplying the product of length and maximum width of leaves by 0.7. Biomass was determined from fresh materials dried in an oven at 75 °C for 48 h. Rice yield was expressed as grain weight at 14% of moisture content.

2.4. Soil data

The ORYZA2000 model has three soil moisture balance modules: PADDY, SAHEL, and SAWAH. PADDY was selected in this study, as it is of moderate complexity and is commonly used for paddy field simulations [23]. The soil data required by PADDY include physical and chemical characteristics such as soil type, composition, texture, water storage capacity, bulk density, and pH. The soil parameters for this regional simulation were collected from the soil data records of experimental sites and Soils of China [24].

2.5. ORYZA2000 model

ORYZA2000 is a dynamic, mechanistic model for rice growth jointly developed by the International Rice Research Institute (IRRI) and Wageningen University. This model simulates 1) potential rice growth, 2) rice growth under water stress, and 3) rice growth under nitrogen stress. It defines four physiological developmental stages: 1) emergence (DVS = 0), 2) panicle initiation (DVS = 0.65), 3) blossom period (DVS = 1) and 4) maturation (DVS = 2) [23].

For simulation, the model uses a daily calculation scheme for the rate of dry matter production and the rate of phenological development. By integration of these rates over time, dry matter production of the crop is simulated throughout the growing season. Total daily rate of canopy CO\(_2\) assimilation is calculated...
by subroutines that integrate instantaneous rates of leaf CO₂ assimilation over time within the canopy, in consideration of daily incoming solar radiation, temperature, and leaf area index. This calculation is based on an assumed sinusoidal variation of radiation over the day and an exponential light profile within the canopy. After subtraction of respiration requirements, net daily growth rate is obtained. The dry matter produced is partitioned among various plant organs. For aboveground parts, the accumulated dry matter is distributed to stem, leaf and panicle. The main influences of rice nitrogen content on photosynthetic efficiency, leaf growth rate, and wilting of leaves. During periods of water stress, the soil–water balance model is activated to simulate leaf rolling, low photosynthetic efficiency, slow development rate, and reduced seed set rate [23]. The ORYZA2000 model also incorporates the effect of CO₂ fertilization by introducing a correction coefficient for the initial light-use efficiency of a single leaf using the following formula developed by Jansen et al. [25]:

\[ \varepsilon = \varepsilon_{340} \left\{ \frac{1 - \exp(-0.00305 \times C_{CO_2} - 0.222)}{1 - \exp(-0.00305 \times 340 - 0.222)} \right\} \]

where \( \varepsilon \) is the leaf CO₂ effect coefficient, \( \varepsilon_{340} \) represents the reference effect value of CO₂ with a concentration of 340 mol L⁻¹ (defined as 1), and \( C_{CO_2} \) is CO₂ concentration in the actual simulation environment.

2.6. Regional simulation schemes

Two experimental schemes (with or without CO₂ fertilization effects) were used to simulate the change of rice yield under the A2 and B2 CO₂ emission scenarios. Scheme I considers only increasing temperature influence on rice growth and yield without an effect of elevated atmospheric CO₂, while scheme II considers the influences of both elevated atmospheric CO₂ concentration and increasing temperature. Each experimental scheme was applied grid square with a spatial resolution of 50 km. For each grid square, input data files for ORYZA2000 were created, containing experimental conditions, crop characteristics, soil properties, and weather data. All model parameter values were read from these files. Model genetic parameter values were calibrated for each representative rice variety. In all experimental schemes, the day when average daily temperature consistently reached 15 °C (using a 5-day moving average method) was set as the seeding date. Rice was transplanted from the greenhouse before seeding. Nitrogen fertilizer (105 kg ha⁻¹ total) was applied four times at transplanting, tillering, jointing and booting stages, accounting respectively for 30%, 30%, 30%, and 10% of total N application, in line with field experimental applications. For irrigated rice, an automatic irrigation system was used to maintain a 75 mm water depth. Mean atmospheric CO₂ concentration at baseline was set at 330 mol L⁻¹, whereas the concentrations in 2010–2050 under the A2 and B2 scenarios were set at 475 and 450 mol L⁻¹, respectively. For the experimental scheme neglecting CO₂ fertilization effects, CO₂ concentration in 2010–2050 was set at the same level as the baseline.

2.7. Yield statistics and analysis

The coefficient of variation (CV) of yield represents the ability of the crop production system to adapt to environmental change. If the CV is near 0, crop production is considered stable. In contrast, a high CV indicates high interannual yield variability [26]. A box plot was used to depict intuitively the discrete levels of yield data.

Using annual simulated data, regional characteristics of rice yield variation were analyzed. The differences in mean yield between baseline and climate change scenarios were tested by one-way ANOVA (\( P < 0.05 \)). The change in rice yield over time was described by the following formula:

\[ y(t) = a_0 + a_1 t \]

where \( y(t) \) is the rice yield (kg ha⁻¹), \( a_1 \) is the rate of yield change, \( t \) is the year, and \( a_0 \) is an intercept. The rate of yield change each 10 years (10\( a_1 \)) is usually used to describe the rate of change of yield in agricultural meteorology. Similarly, the rate of change of meteorological elements (e.g. the trend of average maximum and minimum temperature, °C per 10 years) is also calculated.
In yield analysis, the rate of change of rice yield was described by the following formula [27]:

\[ P_y = \frac{\Delta Y}{Y} \times 100\% \]  

(3)

where \( P_y \) is the rate of change of simulated rice yield (% per 10 years), \( \Delta Y \) is the change of simulated rice yield (10\(^a\), kg ha\(^{-1}\) per 10 years), and \( Y \) is the mean yield on the 40-year baseline (kg ha\(^{-1}\)).

### 3. Results and analysis

#### 3.1. Calibration and validation of the ORYZA2000 model

A large number of parameters are contained in the ORYZA2000 model. In each simulation, most of these could be set to default values. However, parameters reflecting rice heredity and variety characteristics such as development rate, partitioning factors, relative leaf growth rate, specific leaf area, leaf death rate, and fraction of stem reserves require input of experimental data for calibration [14]. In the study, observed data on crop phenological stages, leaf area index (LAI), biomass, grain yield, crop water use, and soil water dynamics from the experimental station in the Heilongjiang province were used to calibrate and validate the ORYZA2000 model. Data collected in 2007 and 2008 were used for calibration and data from 2009 and 2010 were used for validation.

Model validation indicated that the normalized root mean square error for simulated rice yield was less than 21% and that for the above ground biomass was less than 12%, with correlation coefficients of 0.87 and 0.98, respectively (Fig. 2). The absolute error for each simulated development stage was less than 5 days and the average error for the whole growth duration were 1.5 days, suggesting that the ORYZA2000 model could be used to simulate the aboveground biomass, yield, and crop development of cold rice with relatively high accuracy.

#### 3.2. Characteristics of climate change during rice growth

Temperature and precipitation during the rice growing season for the four seasons in the research region under A2 and B2 scenarios relative to the baseline climate were estimated. According to local climate characteristics, winter extends from November to March of the following year, spring extends from April to May, summer extends from June to August, and autumn extends from September to October.

There was a warming trend in annual and seasonal temperatures relative to the baseline climate (1961–1990) in the Heilongjiang province (\( P < 0.05 \)) (Table 1). Mean, maximum, and minimum temperature during summer months would increase (2.0–2.5 °C) compared to the baseline climate. Maximum and minimum temperature increased by 1.8 °C under the A2 scenario and by 2.2 °C under the B2 scenario during the rice growing season. Average maximum and minimum temperatures would increase by 0.6 °C per 10-year period under the A2 scenario and 0.4 °C per 10-year period under the B2 scenario. Annual precipitation during rice growing season was 441 mm in the baseline climate and would increase by 5.4% under A2 scenario and by only 0.5% (not significant) under the B2 scenario. Winter precipitation increased the most, by 35.1% under the A2 scenario and 19.9% under the B2 scenario (\( P < 0.05 \)).

### 3.3. Projected effect of climate change on rice growth

A rise in temperature during the rice growing season might accelerate crop development and reduce the length of the growing season. The simulated changes in rice growing season from 2010 to 2050 under A2 and B2 scenarios compared with those under the baseline climate conditions...
in each region are presented in Fig. 3. The average rice growing season in 2010–2050 under the A2 and B2 scenarios would be shortened significantly ($P < 0.05$) by 4.7 days and 5.8 days, respectively, with a maximum of 10.0 and 11.1 days in the southwest part of the Heilongjiang province (zone III). This result suggests that the growth duration was shortened considerably by the increased temperature of the western Songnen Plain. The growth duration increased progressively with latitude. In zone IV, however, the rice growing season increased by 2.5 and 3.1 days under the A2 and B2 scenarios, respectively. The mean temperature during the rice growing season in the baseline climate was approximately 12.8 °C in zone IV, which was 3.4 °C lower than the mean temperature over all study regions. These lower temperatures greatly affected growth relative to that observed in the baseline climate. However, the mean temperatures during the rice growing season in zone IV under the A2 and B2 scenarios increased by 1.8 °C and 2.1 °C, respectively. Relative to other regions, the temperature increase improved conditions during the rice growing period and the effect on the rice growing season was more obvious, largely compensating for the heat deficiency in rice growth in zone IV. It was thus beneficial to rice growth by extending the growth duration.

### 3.4. Effect of increased temperature on simulated rice yield

In scheme I, the average simulated rice yields for the coming 40 years in the Heilongjiang province were 7842 kg ha$^{-1}$ under the A2 scenario and 7559 kg ha$^{-1}$ under the B2 scenario. The average yields increased by 11.9% under the A2 scenario and 7.9% under the B2 scenario, averages significantly greater than that simulated with the baseline climate ($P < 0.05$). Thus, the simulations suggested that rice yield in this region would increase if temperature increase continued in future decades.

The average yields of zone I under the A2 and B2 scenarios increased by 12.5% and 6.3%, respectively, but by only 2–4% in Hegang and Baoqing (Table 2). In zone II, the simulated yields increased by 15% and 17% under the A2 and B2 scenarios, respectively, but decreased by −5% to −12% in Fujin and Huling. In zone III, the average rice yield was reduced by 5.6% and 9.3% under the A2 and B2 scenarios, respectively. In some areas (Tailai, Qiqihar, Suihua, Anda, etc.), the rice yield was reduced by approximately 9–15%. This was likely a result of the reduced length of the rice growing season in the western Songnen Plain.

The spatial distribution of rice yield change was consistent under the A2 and B2 scenarios relative to the baseline climate (Fig. 4). The area with more than 30% yield increases was in zone IV and the southern region of the Suifenhe Mountains, but the size of the area was less under the B2 than under the A2 scenario (Fig. 4-a, b). The regional pattern of increased yield was similar to the spatial distribution pattern of temperature increase. The area with a yield decrease (−1% to −15%) was mainly in zone III and parts of zone II (the eastern region of the Heilongjiang province) but the size of the area was greater under the B2 scenario than under the A2 scenario (Fig. 4-a, b).

Overall, future warming would be favorable for rice crop growth in higher-altitude areas, but there were some slight decreases in the warmer southwest of Songnen Plain. The average temperature under the A2 scenario during the rice growing season was about 0.4 °C lower than that under the B2 scenario. The simulated average rice yield was 4.0% higher under the A2 than under the B2 scenario. This result suggests that an excessive rise in temperatures during the rice growing season leads to reduction of the growth duration, which in turn reduces the positive impacts of climate change on rice yield. However, the precipitation simulated in the rice growing season under A2 and B2 scenarios also resulted in...
reduced solar radiation, which could be a factor affecting yield change differences.

The changes in simulated yield under A2 and B2 scenarios over the baseline are presented in Fig. 5 and Table 3. Although the difference in increased yield among regions was not significant under the two scenarios, the negative deflection was large. In zone IV, the median increase in yield was 15.8% with a CV of 45.0% under the A2 scenario and was 18.9% with a CV of 43.0% under the B2 scenario. Although these yield increases were the highest in this zone, the variability was also greater. In zone II, the median changes in rice yield were −0.8% and −2.3% under the A2 and B2 scenarios, respectively, with a CV of 41.0%. In zone III, the median changes in rice yield were −1.2% and −2.7% under A2 and B2 scenarios, respectively, with a CV of 0.27%. The yield in zone III was also less variable. In zone I, the median increase in yield was similar (6.4% for A2 and 7.6% for B2 scenarios), but variability was lower under the A2 scenario (CV = 0.36) than under the B2 scenario (CV = 0.42).

The rate of change of simulated rice yield ($P_Y$) in the Heilongjiang province in the next 40 years was 5.0% and 2.5% per 10-year period under the A2 and B2 scenarios, respectively, and the increased temperature markedly affected rice yield (Table 4). The highest increase in $P_Y$ was in zone IV, by 9.5% (A2) and 7.6% (B2) per 10-year period. However, in zone III, $P_Y$ actually decreased by 3.0% per 10-year period. In zones I and II, rice yield increased by 2.2–7.9% per 10-year period.

The increase in $P_Y$ was 3–6% per 10-year period in part of the eastern regions of the Heilongiang province under A2 scenario, whereas it was approximately −6% per 10-year period in Fujin (Fig. 6). The increase in $P_Y$ was 6–10% per 10-year period in the middle of this research region, whereas it was approximately 15% per 10-year period in Yichun and Tonghe. $P_Y$ decreased by −6% to −3% per 10-year period in most parts of the northwestern regions of the Heilongiang province. The abundant heat resources in the western and southwestern of Songnen Plain could also affect rice growth. Under the B2 scenario, the areas of decrease in $P_Y$ expanded markedly relative to the A2 scenario. The lower rate of change of average maximum and minimum temperature during the rice growing season under the B2 than the A2 scenario likely led to lower rates of increase in rice yield.

### 3.5. Effect of increasing atmospheric CO2 on simulated rice yield

With increasing atmospheric CO2, the average simulated rice yields in the Heilongjiang province in the next 40 years were 9867 and 9234 kg ha$^{-1}$ under the A2 and B2 scenarios, respectively, increasing by 44.5% and 35.3% over the baseline period. The simulated rice yield increased by more than 60% in zone IV

### Table 3 – Coefficient of variation (CV) of rice yields in the baseline period (1961–1999) and the period 2010–2050 under A2 and B2 scenarios with and without accounting for increasing CO2 concentration.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Baseline</th>
<th>Scheme I (without CO2)</th>
<th>Scheme II (with CO2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A2 scenario</td>
<td>B2 scenario</td>
<td>A2 scenario</td>
</tr>
<tr>
<td>I</td>
<td>0.55</td>
<td>0.36</td>
<td>0.42</td>
</tr>
<tr>
<td>II</td>
<td>0.49</td>
<td>0.41</td>
<td>0.41</td>
</tr>
<tr>
<td>III</td>
<td>0.36</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>IV</td>
<td>0.55</td>
<td>0.45</td>
<td>0.43</td>
</tr>
</tbody>
</table>

### Table 4 – The mean change trends of simulated rice yields ($P_Y$, % per 10 years) in the period 2010–2050 over the baseline period (1961–1999) under A2 and B2 scenarios with and without accounting for increasing CO2 concentrations in four different rice production regions.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Scheme I (without CO2)</th>
<th>Scheme II (with CO2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A2 scenario</td>
<td>B2 scenario</td>
</tr>
<tr>
<td>I</td>
<td>6.0</td>
<td>2.2</td>
</tr>
<tr>
<td>II</td>
<td>7.9</td>
<td>4.9</td>
</tr>
<tr>
<td>III</td>
<td>−3.0</td>
<td>−3.0</td>
</tr>
<tr>
<td>IV</td>
<td>9.5</td>
<td>7.6</td>
</tr>
</tbody>
</table>
In zones I and II, simulated rice yield increased by 36–50% under A2 and B2. In zone III (southwest part of Songnen Plain) the simulated rice yield increased by 22% and 14% under the A2 and B2 scenarios, respectively, but decreased slightly in scheme I (without accounting for increasing atmospheric CO2). These simulations indicated that elevated atmospheric CO2 concentrations had a clear and positive effect on subsequent rice yield. However, the simulation models also indicated obvious differences between areas of the Heilongjiang province. In zone IV, the contribution of increasing atmospheric CO2 to rice yield was the largest, at 45% and 33% under the A2 and B2 scenarios, respectively. In zone I, this contribution resulted in 34% and 30% increases, in zone II 32% and 27%, and lastly in zone III, 28% and 23%, respectively. The positive effect of increasing atmospheric CO2 was the greatest in higher-altitude, low-temperature mountainous regions. In areas with adequate temperatures this simulated positive effect was smaller.

By comparison with simulations without increasing CO2 concentration (Fig. 4), the area with simulated rice yield increased by more than 30% was dramatically expanded (Fig. 7). The areas of simulated rice yield decrease without consideration of CO2 fertilization (Fig. 4) disappeared. The contribution of increasing atmospheric CO2 was 25–33%, but there still was a marked dispersion in the simulated rice yield and a clear risk of low yield (Figs. 5 and 8).

The CV of yield was lower than that in the baseline in both schemes under the A2 and B2 scenarios (Table 3). In scheme I, the CV was 37% and 39% under the A2 and B2 scenarios, respectively, and decreased by 12% and 10% compared with that in the baseline climate. In scheme II, CV was 35 and 38% under A2 and B2 scenarios, respectively, and decreased by 13% and 11% compared with that in the baseline. There were no obvious differences in CVs between schemes I and II. The CV decreased the most in zone I, by 18.2% and 13.1% under the A2 and B2 scenarios, respectively. The simulation models suggested that the combination of increased temperature and increased atmospheric CO2 would improve rice yield stability in the future climate.

The increase in $P_Y$ was small at 5.4% and 2.6% per decade under the A2 and B2 scenarios, respectively. $P_Y$ was similar under these two scenarios relative to that simulated in
scheme I (Table 4), but there was a slight increase. The spatial distribution of $P_Y$ with CO$_2$ fertilization under the A2 and B2 scenarios is presented in Fig. 9. The area of increased yield each next 10 years expanded relative to that simulated in scheme I (Fig. 6). These results also indicate that climate change (increasing temperature and atmospheric CO$_2$) would still have a clear and positive effect on rice yield in most regions of the Heilongjiang province in the next 40 years. However, it was obvious that the positive effect was small if the same cropping system continued.

4. Discussion

According to the fourth IPCC assessment, the average global temperature has risen 0.74 ± 0.18 °C in the past 100 years, along with continuous emissions of greenhouse gases [14,28,29]. Recent studies have shown a negative impact of warming on crop production as warming shortened the crop growth period (especially the post-flowering period) [26,30–32]. For example, in China, the warming trend from 1981 to 2000 had negative effects on crop yield at several representative stations (e.g. Tianshui, Changsha, Hefei, and Zhengzhou) [32]. A 1.8 °C increase in wheat growing season temperature reduced wheat yields by about 3–10% in China during 1979–2000 [33]. The effect of the warming trend on crop yield in this study is much larger than in the above studies, reducing yield by 16.2–28.4% with a 1 °C increase in wheat growing season maximum temperature. These results may be because the optimum temperatures of spring wheat, naked oat and potato in the Northern Agro-pastural Ecotone of China were 18–22 °C, 18–20 °C, and 16–18 °C, respectively [34–36]. However, the annual growth season maximum temperature during 1990–2009 was approximately 22.1 °C. Liu et al. [34] and Liu et al. [35] showed that as plant photosynthetic organs of spring wheat and naked oat in the filling stage gradually vestigial, higher temperature increases dry matter consumption, resulting in a yield decline. Sun et al. [36] reported that higher temperature is harmful at the potato flowering and tuber expansion stages, reducing potato yield. Thus, increasing temperature shortens the crop growth period (especially the post-flowering period) in the NAE, resulting in incomplete grain or tuber filling.
However, most researchers have focused only on the effect of warming on crop production, while ignoring the effect of CO₂ fertilization. Tao et al. [21,37] proposed that the effects of temperature and CO₂ concentration on physiological processes and mechanisms governing crop growth and production should be separately investigated. In the present study, two experimental schemes were followed using the ORYZA2000 model to simulate the impact of future climate change on cold rice yield in the Heilongjiang province. The analyses were focused on the effects of temperature increase and CO₂ fertilization on cold rice production in the next 40 years. They suggested that crop production would increase by 7.9–11.9% if increase in atmospheric CO₂ was not considered, whereas productivity would increase by 31.3–44.5% if rising CO₂ was factored into the model. Simulations with elevated CO₂ indicated that the negative effect of temperature rise on cold yield in some regions could be offset by CO₂ fertilization. These results differ from those of other studies investigating potential effects of climate change on rice yield in the lower reaches of the Yangtze River and southern regions of China [8,13–16,28]. As crop production in cold regions is limited by lower temperature, increasing temperatures may increase crop production [31,38]. However, there are still few studies investigating the effect of climate change on cold rice production in cold regions and its potential yield. Thus, the present study fills a knowledge gap and will be important for increasing cold rice yield in the future.

However, although our assessment of the impact of climate change on cold rice is based on a validated rice simulation model, some sources of uncertainty may influence our results. The ORYZA2000 model accounts for the effect of CO₂ fertilization by applying a correction coefficient to the initial light-use efficiency of single leaves. However, Bannayan et al. [39] pointed out that the ORYZA2000 model may greatly overestimate the increase in peak green leaf area index due to elevated CO₂ concentration and also fails to reproduce accurately the observed interactions between nitrogen and rice yield response to increasing atmospheric CO₂. In addition, the method for selecting the predominant soils for each grid square may fail in mountainous areas where soils are unsuitable for agriculture.

In spite of the many uncertainties in our schemes, the results are in reasonable agreement with those of similar studies [8,13–16,28], as well as filling a knowledge gap with respect to the effect of climate change on cold rice production. They show that future climate change will significantly affect the rice production, with shortened growth period and increased spatial variation in rice yield. However, the effect of climate change on rice yield simulated in this study differs from that in similar studies [8,13–16,28] as our results show that climate change in the future will favor cold rice production in most regions and that CO₂ fertilization may offset the negative effect of warming.

5. Conclusion

The study suggests that the climate in the Heilongjiang province will become more warm and humid in the next 40 years. This change would very likely be beneficial for cold rice yield and its stability. Zhang et al. [26] described the importance of exploring the adaptation of agronomic management strategies for ensuring food security in the future climate condition. Adaptation strategies such as using rice cultivars with long growth duration and using alternative planting patterns and associated management practices should be considered in cold rice production. In addition, as the duration and intensity of extreme weather events increase, a greater understanding of response to climate would be of high value for maintaining adequate cold rice production.

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References


