Modeling Climate Change Impacts on Rice Growth and Yield under Global Warming of 1.5 and 2.0 °C in the Pearl River Delta, China

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Abstract: In this study, the potential climate change impacts on rice growth and rice yield under 1.5 and 2.0 °C warming scenarios, respectively, are simulated using the Ceres-Rice Model based on high-quality, agricultural, experimental, meteorological and soil data, and the incorporation of future climate data generated by four Global Climate Models (GCMs) in the Pearl River Delta, China. The climatic data is extracted from four Global Climate Models (GCMs) namely: The Community Atmosphere Model 4 (CAM4), The European Centre for Medium-Range Weather Forecasts-Hamburg 6 (ECHAM6), Model for Interdisciplinary Research On Climate 5 (MIROC5) and the Norwegian Earth System Model 1 (NorESM1). The modeling results show that climate change has major negative impacts on both rice growth and rice yields at all study sites. More specifically, the average of flowering durations decreases by 2.8 days (3.9 days), and the maturity date decreases by 11.0 days (14.7 days) under the 1.5 °C and (2.0 °C) warming scenarios, respectively. The yield for early mature rice and late mature rice are reduced by 292.5 kg/ha (558.9 kg/ha) and 151.8 kg/ha (380.0 kg/ha) under the 1.5 °C (2.0 °C) warming scenarios, respectively. Adjusting the planting dates of eight days later and 15 days earlier for early mature rice and late mature rice are simulated to be adaptively effective, respectively. The simulated optimum fertilizer amount is about 240 kg/ha, with different industrial fertilizer and organic matter being applied.

Keywords: adaptive measures; climatic change; CO₂ fertilization effect; Guangdong Province; Ceres-Rice Model; rice production
1. Introduction

It is well known that the average global temperature has continued to increase since the industrial revolution [1–3], with an increase by 0.87 °C during the period 2006–2015, compared with the historic period 1850–1900 (pre-industrial level) [4–7].

The Paris Agreement requires that all signatories should hold the global average temperature increase at no more than 2.0 °C above preindustrial levels, and pursue further efforts to limit this increase below 1.5 °C [8–10]. The Intergovernmental Panel on Climate Change (IPCC) has published a special report in 2018 on the impacts of global warming of both 1.5 and 2.0 °C above the preindustrial levels [11]. The negative impacts of climate change on ecological- and agricultural-related crop yields have been of great concern, because the reduction of crop yields will possibly further raise certain issues, such as food crises that will endanger the regional stability of society [12–14]. Crop yields are closely related to food security, and a reduction in yields would likely exacerbate the global food crisis profoundly [15]. Therefore, assessing the impacts of Climate Change (CC), especially for the 1.5 and 2.0 °C warming scenarios on crops, is urgently needed [16,17].

The IPCC’s Representative Concentration Pathways (RCPs namely, RCP2.6, RCP4.5, RCP6.0, and RCP8.5) are commonly used to assess potential climate change impacts on crop yield [18–20]. The climatic information extracted from these RCPs is used to simulate crops yields in the agricultural and ecological models, with the cultivar parameters being held constant [21,22]. Many researchers have evaluated various types of simulations using crop-based models, obtaining the impacts on crops according to spatial and temporal scales. These researchers have contributed to the increasing of crop yield through adaptive measures. Yin et al. simulates the yields of major crops in China using a combined multi-model analysis method, for which the climatic data from 2006 to 2099 are utilized from the Fifth Coupled Model Inter-comparison Project (CMIP5) [23]. Xu et al. explores the impacts of climate change on the flowering and maturity durations of rice in the Sichuan Basin, China [24]. The change of flowering and maturity durations indicates the less accumulation of dry matter, which means less yield. Their results show that under the climate change impacts from CMIP5, rice yields would inevitably decrease. Li et al. simulates rice yields during three future periods (2011–2040, 2041–2070, and 2071–2099) in Hunan Province with climate data generated by five General Circulation Models under the RCP4.5 and 8.5 scenarios [25]. These studies have reached broad conclusions that the increase of temperature could shorten the duration of the flowering and maturity of crops, then reduce the yields dramatically. However, some of the mentioned results are based upon climatic information extracted from the CMIP5, in which the climatic change scenarios are not so close to the recent facts, such as the growing warming and decreasing precipitation. Furthermore, the CO₂ fertilization effect is seldom accounted for, and the optimal management processes are rarely identified.

The Half a Degree Additional Warming Projections, Prognosis and Impacts (HAPPI) experiment aims to provide the climate data for the next generation, describing the climatic conditions that are 1.5 and 2.0 °C warmer, respectively, than the pre-industrial conditions. In other words, the project provides the climatic data that describes how the weather data differ from the pre-historic situations when the temperature is 1.5 and 2.0 °C warmer. The key challenge of this project is to separate the impact of an additional approximately half degree of warming from uncertainty in climate model responses and internal climate variability that dominates CMIP-style experiments under low emission scenarios. The HAPPI is actually a new climate model that has been developed from the RCPs. To be more specific, the RCP2.6 is used to provide the model boundary conditions for the 1.5 °C scenario, and a weighted combination of RCP2.6 and RC P4.5 for the 2.0 °C scenario. HAPPI has been developed to explicitly inform one of the primary aims of the Paris Agreement, which seeks to understand impacts of a world limiting global-averaged warming to 1.5 °C. The bias-corrected or raw formats dataset is already available, and this dataset is ready for direct input to a range of common climate-impact models. The HAPPI is a Global Climate Model (GCM); all data are given in the form of their geographic location. All climatic data can be extracted according to the known longitude and latitude. The closest grid can be replaced if the grid has no climatic data. So far, the HAPPI is the only climatic model
available that can be directly used in simulation models that assess the impacts of climate change from the 1.5 and 2.0 °C scenarios. The newly released 1.5 and 2.0 °C (2106–2115) warming scenarios are climate change projections of temperature, precipitation and sunshine hours compared with RCPs integrated in the CMIP5. In addition, the increases of 1.5 and 2.0 °C above preindustrial levels reflect a more moderate climate scenario, and only a few studies have used the new scenario to assess the potential climate change impacts on crops globally. Chen et al. evaluates the impacts of climate change and climate extremes on major crops in China at global warming levels of both 1.5 and 2.0 °C [26]. Jacob et al. explores the climate impacts for the coming decades in Europe under a global warming level of 1.5 °C [27]. These studies stated above have mainly explored the impacts on food production by using the RCPs generated from the CMIP5 in China; however, little information is known regarding the degree to which climate change will have an impact on China under a moderate temperature increase. Some circumstances exist with uncertainties, because the real impacts would always be eliminated or neglected when the scale is upgraded to a moderated large-scale region. Therefore, it is of vital importance to use site-based experiments to explore the real impacts of climate change under the 1.5 and 2.0 °C warming scenarios using high resolved data, providing useful information to guide the management of crops in regional areas.

China is one of the major producers of staple foods such as rice, wheat and maize [28–30]. The total crop production in China accounts for about 20 % of all global production [31]. The Pearl River Delta (PRD) is a main agricultural production base in China, of which the main crop is rice [32]. Therefore, the need of assessing the potential climate change on crops under the 1.5 and 2.0 °C warming scenarios in this region still exists. This is especially the case when extreme climatic conditions would likely reach the maximum allowable threshold for crop growth, which will bring negative effects. The objectives of this study are to (1) assess the impacts of potential climate change on rice under the 1.5 and 2.0 °C warming scenarios in the PRD, China, and (2) optimize regional management operations, such as planting dates and the use of fertilizer, to face this potential challenge.

2. Methods

2.1. Study Area

The Pearl River Delta (PRD) is the main rice production area in China, and the population density is relatively high, and the rice production in this area has reached 1,000 million tons [33–35]. Both early mature and late mature rice are cultivated, and therefore, the rice is planted twice per year. Typically, the early mature rice is grown in March, and the late mature rice is grown in June. Most of the PRD is in the subtropics, and only a small proportion is in the actual tropics; also it lies in the southernmost part of China, which means it is nearer to the equator than the other rice production areas in China [36]. Therefore, the global warming trend will influence the rice production in this area more intensely than in other areas. The National Meteorological Information Center (NMIC) has established a number of Agrometeorological Experimental Stations (AES) for observation and collection of crop development data involving the climate, crop phenology, and management across the cultivation areas through a standard procedure. Figure 1 shows all the sites: Chaozhou (CZ), Gaoyao (GY), Heyuan (HY), Huazhou (HZ), Lianzhou (LZ), Lufeng (LF), Meixian (MX), Qujiang (QJ), Guangzhou (GZ), Xuwen (XW), Yangjiang (YJ) and Zhongshan (ZS) that are located in the PRD. The rice is divided into ‘early mature rice’ and ‘late mature rice’ by the planting dates. For early mature rice, the site and the corresponding rice cultivars are: CZ (Teyou254), GY (Xuehuanian), HY (Zayou), HZ (Qishanzhan), LZ (Jinyou207), LF (YouI402), MX (Meiyou6), QJ (Jufengnian), GZ (Meixiangzhan), XW (Gaokang999), YJ (Zayou) and ZS (Tainanzhan). For late mature rice, the site and the corresponding rice cultivars are: CZ (Xieyou3550), GY (Xuehuanian), HY (Zayou), HZ (Gaozhoubaiqiu), LZ (Jinyou253), LF (Yueyou350), MX (Meiyou6), QJ (Baikenian), GZ (Teshan25), XW (Boyou15), YJ (Zayou) and ZS (Tainanzhan).
The GDD is calculated by a judgement of a function that is described in the following equation [50]:

\[
GDD = \begin{cases} 
T - T_{\text{base}} & \text{for } T_{\text{base}} < T < T_{\text{opt}} \\
T_{\text{high}} - T & \text{for } T_{\text{opt}} < T < T_{\text{high}} \\
0 & \text{for } T < T_{\text{base}} \text{ or } T > T_{\text{high}}
\end{cases}
\]  

(1)

In the equation, \( T_{\text{base}} \), \( T_{\text{high}} \) and \( T_{\text{opt}} \) represent the baseline, extremely high and optimal temperatures, respectively [51].
When the temperature falls between the baseline and the optimal temperature, the rice will attain the highest production. However, when the temperature falls between an extremely high or low temperature, the rice will hardly survive.

2.2.2. Model Input

(a) Climatic Data

The historic daily climate data, including sunshine hours, minimum temperature, maximum temperature and precipitation during the crop growth periods, are acquired from the China Meteorological Administration (CMA) [52,53]. The CMA can provide high resolution weather data of 699 sites all over the country [54]. The site-based data within the range of the PRD is used for the calibration of the Ceres-Rice Model.

The future climatic variables for the 1.5 and 2.0 °C warming scenarios are generated from the Half a Degree Additional Warming Projections, Prognosis and Impacts (HAPPI) experiment. This data set is published by the National Energy Research Scientific Computing Center (NERSCC), and includes four Global Climate Models (GCMs), namely The Community Atmosphere Model 4 (CAM4), The European Centre for Medium-Range Weather Forecasts-Hamburg 6 (ECHAM6), The Model for Interdisciplinary Research On Climate 5 (MIROC5) and The Norwegian Earth System Model 1 (NorESM1) [16]. The spatial resolution of these data is 0.5 of a degree, and the temporal resolution is every 24 h. These data are used to assess the potential climate change of 1.5 and 2.0 °C warming scenarios. The climatic variables from global warming of 1.5 and 2.0 °C are actually the global average warming of 1.5 and 2.0 °C. Therefore, the regional warming may be far different from the global warming of 1.5 and 2.0 °C. To obtain the regional climatic variables in the PRD, the site-based location is used to extract the corresponding climatic variables. These models are able to provide the climatic information on global averages of 1.5 and 2.0 °C warmer than the preindustrial level. MIROC5 provides 10 runs of the simulations, and CAM4, ECHAM6 and NorESM1 each provide 20 runs of the simulations. Therefore, there are 700 years of climatic data (1 GCM × 10 runs × 10 years × 3 GCMs × 20 run × 10 years = 700) for one site. These results are based upon large sets of simulations (>50 members) of atmosphere-only models for three time periods. The first is from 2006 to 2015, which is considered the historic or baseline scenario. The second is a similar decade, but is 1.5 °C warmer than the preindustrial (1861–1880) level scenario. Similarly, the third is a similar decade, but 2.0 °C warmer than the preindustrial (1861–1880) level scenario. The second and the third scenarios are called the 1.5 and 2.0 °C warming scenarios (2106–2115), respectively. Detailed information on the publishing institute and the members of each GCM are given in Table 1.

Table 1. The detailed information of the Global Climate Models (GCMs) used in the Half a Degree Additional Warming Projections, Prognosis and Impacts (HAPPI).

| GCM      | Publishing Institute                                                                 | Horizontal Resolution | Ensemble Members |
|----------|---------------------------------------------------------------------------------------|-----------------------|------------------|
|          |                                                                                       |                       | 2006–2015 2106–2115 (+ 1.5 °C) 2106–2115 (+ 2.0 °C) |
| ECHAM6-3-LR | Max Planck Institute for Meteorology, Hamburg, Germany; Deutsche Klimarechenzentrum, Hamburg, Germany | 2.813 × 2.791°       | 20 20 20 |
| NorESM1-HAPPI | NorESM (Norwegian Earth System Model) climate modeling consortium                     | 1.250 × 0.940°       | 20 20 20 |
| CAM4-2degree | ETH, Zurich, Switzerland                                                               | 2.000 × 2.000°       | 20 20 20 |
| MIROC5   | Atmospheric and Ocean Research Institute, University of Tokyo, Chiba, Japan; National Institute for Environmental Studies, Ibaraki, Japan; Japan Agency for Marine-Earth Science and Technology, Kanagawa, Japan | 2.813 × 2.791°       | 10 10 10 |
(b) Soil Data

Soil information from each site is acquired from the China Soil Scientific Database (CSSD) according to site locations, respectively [55,56]. The soil information contains the basic physical properties that are crucial for the rice growth, that includes the soil color, slope, pH, runoff potential, fertility factor, organic matter and cation exchange capacity. Typically, the soil is divided into four layers according to the soil depth of each site. The thickness of the soil in this region is 100 cm, and the typical pH is from 5 to 7 (acidic to neutral) [57]. The soil information is the basic input data that is used to calibrate and validate the Ceres-Rice Model, which is further used to identify the rice parameters [37]. The detailed soil information of each site is given in Table A1.

(c) Crop Management Options

China has been paying great attention to the observation and collection of the crop growth, management records and yields in more than 600 AES established by NMIC. Typically, the data involves the weather, crop phenology and management across the cultivation areas [58,59]. The agricultural management records containing the planting, transplanting date, crop emergence, flowering and maturity dates, the cultivar type, yields and management practices, as well as the detailed information of the sowing depth and the planting density. These data can be transformed into flowering duration (the number of days from the transplanting date to the flowering date) and the maturity duration (the number of days from the transplanting date to the maturity date). These are required as the input data in the Ceres-Rice Model. The detailed information of the crop management options of each site is shown in Table A2.

2.2.3. Model Parameterization

Model Parameterization calculates the coefficients of each crop cultivar, in other words, the whole process is called “model localization” [60]. The mentioned rice coefficients defined in the Ceres-Rice Model that control the growth of the crop are each calculated for each site, with one particular crop cultivar and the site-based management records. Parameterization can be divided into two main processes: Model calibration and model validation [61]. Model calibration is to obtain the coefficients, and model validation is to test the reliability of the obtained coefficients. Commonly, the growth coefficients are calculated using records such as flowering duration, maturity duration and yield. These records should be selected without pest, water or heat stress. One year of data is used to calibrate the model, and the other two years of data are used to validate the model. Each rice station is independently calibrated and validated to acquire the most precise station-specific and cultivar-specific rice coefficients in order to verify more accurate simulation results [62]. Then, the calibrated station-specific and cultivar-specific rice coefficients are used for the model evaluation, which aims to assess the growth of the crop under the 1.5 and 2.0 °C warming scenarios.

The Generalized Likelihood Uncertainty Estimation (GLUE) is developed to obtain the coefficients in the Ceres-Rice Model [63]. To test the reliability of the coefficients, the Normalized Root Mean Square Error (NRMSE) is introduced:

\[
\text{NRMSE} = \frac{1}{\bar{O}_i} \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}}
\]  

(2)

In the equation, \(S_i\) represents the simulated variables using the model with coefficients, and \(O_i\) represents the observed variables at each site, while \(\bar{O}_i\) is the average of the observed data involved, then \(n\) is the number of all the data, and \(PD_i\) is each relative error. It is commonly believed that when NRMSE is less than 10%, between 10% and 20%, and between 20% and 30%, the calibration result is considered as perfect, good and moderately well, respectively [64].
2.2.4. Simulating the Impact of Climate Change on Rice Crop

The four GCMs are used to extract site-based climatic information according to specific site locations, respectively. The climatic information is set as the only change variable in the model. MIROC5 model provides only 10 runs of the climate simulations, thus it can produce 10 simulation results of rice growth and yield. In all likelihood, the other three models can provide 20 simulation results for each site. The rice cultivar and rice parameters are obtained and given for both early mature and late mature rice.

When simulating the impacts of climate change upon rice, the planting date, irrigation date, fertilization date and rice cultivar at each site are held constant as before. These data are integrated into the model, with each of the rice parameters to simulate the potential growth process of rice under the 1.5 and 2.0 °C warming trends. The results of the GCM ensembles are averaged to obtain the final simulation results. The CO₂ fertilization effect will influence the yield profoundly; to some extent, the higher the CO₂ concentration, the higher the yield will be [26]. In order to assess the CO₂ fertilization effect, the simulation is also completed by using the present and future potential concentrations of CO₂. To assess the CO₂ fertilization effect, the future CO₂ concentration of each year is acquired from the Representative Concentration Pathway (RCP) Database [65].

The flowering date, maturity date, cultivar and rice yield of each site acquired under the 1.5 and 2.0 °C warming scenarios are compared with the results acquired under the baseline time. The simulated yields could be obtained with these data with and without the CO₂ fertilization effect. The comparison is defined in the following equation:

\[ Y_c = Y_a - Y_b \]  

In the equation, \( Y_a \) represents the results under the 1.5 and 2.0 °C warming scenarios, and \( Y_b \) represents the results under the baseline time period [66]. Variable \( Y_c \) represents the change between the warming scenarios and the baseline time.

2.2.5. Simulating Adaptive Measures to Increase Rice Yield

Adaptive measures are intended to change the present management operations to reduce the potential negative impacts from climate change [67]. In order to face this challenge, the fifth Intergovernmental Panel on Climate Change (IPCC) report has suggested several adaptation strategies, such as adjusting planting dates, replacing with more suitable cultivars, breeding new cultivars, improving crop management practices related with optimizing irrigation and fertilizing [68]. In this study, the adaptive measures are simulated in the Ceres-Rice Model, containing the adjusting of planting dates and identifying the optimal use of fertilizer [69]. These two adaptive measures are commonly used and are quite implementable [70]. These two methods are also considered as the most useful and suitable when dealing with the challenge of potential climate change, because the two practices can easily be controlled and performed by normal farmers using the present scientific technologies [25]. The conditions with the highest yields are believed to represent optimized management practices.

The planting date is always considered to be more important than the planting density; thus, the planting date should be optimized to better address the challenges of climate change [71,72]. Changing the planting date is mainly used to alter the phenology of crops to better adapt to a changing environment. To obtain the most optimal planting dates for each site, other interference factors are maintained unchanged. For a given site, the planting date is set as the only changing variable, by identifying the optimal planting dates for early mature rice and late mature rice at each site. The planting date is set by advancing and delaying the planting dates at intervals of five days over the total period of 40 days. Therefore, the planting date with the highest rice yield is viewed as the most optimized planting date [73]. The planting dates of each site are confirmed for early mature rice and late mature rice, respectively.

As for the use of fertilizers, this use is changed from 60 to 300 kg/ha at intervals of 50 kg. In addition, for a given rice cultivar at one site, the date of performing fertilizers is the average of local practice,
and the use of fertilizer is commonly divided into three periods to meet the nutritional needs of rice at every growth stage. Each planting date and each step of fertilizer usage is set as the x-axis, and each of the corresponding rice yields is listed as the y-axis. In order to identify the optimized use of fertilizer of each site, the change of yield and change of fertilizers are calculated using the following equation:

\[
\Delta \phi = \left| \frac{\Delta \text{yield}}{\Delta \text{fertilizer}} \right| \tag{4}
\]

In the equation, \(\Delta \text{yield}\) and \(\Delta \text{fertilizer}\) represent the change of yield and the change of fertilizer, respectively. When \(\Delta \phi\) reaches the highest level, the effectiveness will also be the highest. In this way, the optimal used of fertilizer could be identified. Fertilizer usage is finally confirmed by averaging the yields of all sites.

2.3. Analysis of Climatic Variables and Rice Yields

In the Ceres-Rice Model, the rice yields are closely connected with the climatic variables, such as temperature, sun radiation and precipitation. The relationship between climatic information and rice yield is introduced in the following equation [37]:

\[
\text{yield} = a \times R + b \times \text{TM} + c \times \text{TN} + d \times P + \Delta \tag{5}
\]

In the equation, yield represents the reduced rice yield; \(R\) represents the average of daily solar radiation; \(\text{TM}\) represents the highest daily average temperature, \(\text{TN}\) represents the lowest daily average temperature; \(P\) represents the precipitation and \(\Delta\) is a constant. The \(a, b\) and \(c\) are the correlation coefficients of the climatic variables. These variables are integrated to influence the rice yields in a combinatorial manner.

Pearson Correlation (PC) describes the trend of two groups of data changing and moving, so it is often used in a user-based collaborative filtering system [74,75]. Therefore, the method is used to analyze the relationship between the climatic variables and the rice yields. The climatic variables are used together to build a function with the yields. The Pearson Correlation Coefficient (PCC) of each independent variable is given in the following equation:

\[
\text{Correlation}(x, y) = \frac{(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum(x_i - \overline{x})^2 \sum(y_i - \overline{y})^2}} \tag{6}
\]

In the equation, the \(x\) and \(y\) are two variables, \(x_i\) represents each \(x\), and \(y_i\) represents each \(y\). The \(\overline{x}, \overline{y}\) each present the average of \(x\) and \(y\).

3. Results

3.1. Calibration and Validation of Models

The detailed information of validation results is shown in Figure 2. The calculated NRMSEs using observed and simulated variables (flowering durations, maturity durations and yields) are 12.28% (18.05%), 13.13% (16.63%) and 11.38% (15.27%) for early (late) mature rice, respectively.

For early mature rice, the NRMSEs are no more than 15%, which indicates a relatively perfect model performance. For late mature rice, the NRMSEs all exceed 15% but are less than 20%, indicating a good model performance. Considering the various cultivars and agronomic management practices, this indicates that the model has a moderate high precision and the performance of the model is acceptable for simulating rice growth and rice yields. The detailed information of rice cultivar and corresponding coefficients are given in Table A3.
3.2. Changes in Climatic Variables Under the 1.5 and 2.0 °C Warming Scenarios

The temperature, precipitation, solar radiation and projected CO₂ concentration of the entire PRD under the baseline time and the 1.5 and 2.0 °C warming scenarios are shown in Table 2. The four models are used to extract the regional climate information, and the results are averaged to visualize the potential changing trend of this region. Detailed information of the changing climatic variables are given in Tables A4–A6. The maximum temperature, minimum temperature, precipitation and sunshine hours of the PRD are projected to increase by 0.65 °C, 0.66 °C, 0.20 mm and 0.61 h under the 1.5 °C warming scenario, respectively. The maximum temperature, minimum temperature, precipitation and solar radiation of the PRD are projected to increase by 1.11 °C, 0.97 °C, −0.62 mm and 0.69 h, under the 2.0 °C warming scenario, respectively.

Table 2. Change in climatic variables under the 1.5 and 2.0 °C warming scenarios relative to the baseline time.

| Warming Scenario | TM (°C) | TN (°C) | P (mm) | R (h) | CO₂ (ppm) |
|------------------|---------|---------|--------|-------|-----------|
| 1.5 °C           | 0.65    | 0.66    | 0.20   | 0.62  | 423.4     |
| 2.0 °C           | 1.11    | 0.97    | 0.62   | 0.69  | 486.6     |

1 TM, TN, P, and R represent the maximum temperature, minimum temperature, precipitation and sunshine hours, respectively.
The low, medium, and high CO\(_2\) concentrations are 399 (423.4), 423.4 (486.6) and 486.6 (590) ppm for the 1.5 \(^\circ\)C (2.0 \(^\circ\)C) warming scenarios. Since the 1.5 and 2.0 \(^\circ\)C warming scenarios are moderate scenarios, thus the medium CO\(_2\) concentrations are selected as climatic variables.

### 3.3. Impacts of Climate Change on the Growth Stages of the Rice Crop

The average of the flowering durations for early mature rice of all sites decreases by 4.1 and 6.3 days under the 1.5 and 2.0 \(^\circ\)C warming scenarios, respectively. The average of flowering durations for late mature rice decreases by 1.1 to 5.6 days and 2.0 to 7.6 days under the 1.5 and 2.0 \(^\circ\)C warming scenarios, respectively. In addition, the average of the flowering durations of late mature rice at all sites is projected to decrease by 2.8 and 3.9 days under the 1.5 and 2.0 \(^\circ\)C warming scenarios, respectively. It can be concluded that climate change under the 2.0 \(^\circ\)C warming scenario reduces more days than do the flowering durations under the 1.5 \(^\circ\)C warming scenario. In other words, the potential impacts from climate change on the flowering durations under the 2.0 \(^\circ\)C warming scenario would lead to a more obvious reduction of the flowering durations than under the 1.5 \(^\circ\)C warming scenario. Also, the average flowering durations of early mature and late mature rice show that the impacts of warming climatic conditions would have a much greater impact on the early mature rice than on the late mature rice.

From Figure 3, it is indicated that the maturity durations of early mature rice would decrease 2.9 to 7.6 days under the 1.5 \(^\circ\)C warming scenario. Similarly, the maturity durations of early mature rice decreased 4.4 to 11.8 days under the 2.0 \(^\circ\)C warming scenario. The average maturity durations of early mature rice decreased by 4.8 and 7.4 days under the 1.5 and 2.0 \(^\circ\)C warming scenarios, respectively. The maturity durations of late mature rice decreased from 0.6 to 33.0 days under the 1.5 \(^\circ\)C warming scenario and from 1.4 to 40.6 days under the 2.0 \(^\circ\)C warming scenario. The average maturity durations of early mature rice decreased by 11.0 and 14.7 days under the 1.5 and 2.0 \(^\circ\)C warming scenarios, respectively.

The results of each corresponding site are given in the format of percentage forms to explore the change in the flowering durations and maturing durations. The results in Figure 4 show that all sites are undergoing reductions in flowering and maturing durations. The range is from 3 to 26 days, and the most obvious reductions occurred at the sites LZ, MX and XW. The results also indicate that the climate change impacts on rice phenology are all obvious. The flowering durations are reduced, and will further cause the reduction of yield eventually.

![Figure 3](image-url)

**Figure 3.** Changes in the flowering durations and maturity durations under the 1.5 and 2.0 \(^\circ\)C warming scenarios relative to the baseline time for (a,c) early mature rice and (b,d) late mature rice.
The results of each corresponding site are given in the format of percentage forms to explore the change in the flowering durations and maturing durations. The results in Figure 4 show that all sites are undergoing reductions in flowering and maturing durations. The range is from 3 to 26 days, and the most obvious reductions occurred at the sites LZ, MX and XW. The results also indicate that the climate change impacts on rice phenology are all obvious. The flowering durations are reduced, and will further cause the reduction of yield eventually.

3.4. Impacts of Climate Change on Rice Yields

3.4.1. Impacts of Climate Change on Rice Yields without the CO₂ Fertilization Effect

The simulated yields of early mature rice and late mature rice are shown in Figure 5. The results show that rice yields would be inevitably reduced under both the 1.5 and 2.0 °C warming scenarios compared with the baseline time. Climate change under both 1.5 and 2.0 °C warming scenarios would reduce more yields at nearly all sites for early mature rice. In addition, the rice yields would decline more under the 2.0 °C warming scenario than under the 1.5 °C warming scenario, except for the early mature rice at site GY. The yields of early mature rice are reduced by 1.2 to 758.3 kg/ha under the 1.5 °C warming scenario, and reduced by 12.9 to 916.8 kg/ha under the 2.0 °C warming scenario, whereas the yields of late mature rice are reduced by 11.2 to 280.6 kg/ha under the 1.5 °C warming scenario, and reduced by 2.8 to 937.9 kg/ha under the 2.0 °C warming scenario. The average yield reduction of early mature rice is 292.5 kg/ha for 1.5 °C warming scenario, and is 558.9 kg/ha for 2.0 °C warming scenario. Similarly, there are 151.8 kg/ha for 1.5 °C warming scenario and 380.0 kg/ha for 2.0 °C warming scenario for late mature rice.
When the CO2 fertilization effects are considered, the rice yields increase to some extent, but still could not make up for the total negative impact from climate change. Figure 6 shows the simulated yield difference under the 1.5 and 2.0 °C warming scenarios relative to the baseline time. For early mature rice, the yield difference ranges from 53.9 to −595.3 kg/ha under the 1.5 °C warming scenario, and also ranges from −36.4 to −916.8 kg/ha under the 2.0 °C warming scenario. The average yield differences of early mature rice are −202.0 and −519.3 kg/ha under the 1.5 and 2.0 °C warming scenarios, respectively. For late mature rice, the yield difference ranges from 66.5 to −284.8 kg/ha under the 1.5 °C warming scenario and from 44.3 to −488.4 kg/ha under the 2.0 °C warming scenarios. The average yield differences of late mature rice are −98.9 and −314.0 kg/ha under the 1.5 and 2.0 °C warming scenarios, respectively.

3.4.3. Analysis of the Relationship between the Climatic Variables and Rice Yields

The analysis of the relationship between the climatic variables and rice yields are conducted using the Pearson Correlation introduced in Equation (5). Climatic variables are set as independent variables, and the reduction of rice yields are set as dependent variables. The results are shown in Table 3.
Table 3. The relationship between climatic variables and rice yields.

|                  | a     | b      | c       | d       |
|------------------|-------|--------|---------|---------|
| 1.5 °C_early mature rice | -1647.591 | 10285.218 | -7357.137 | -6962.957 |
| 1.5 °C_late mature rice    | -5466.918 | 3389.475  | 2751.96  | -8846.68  |
| 2.0 °C_early mature rice    | -1900.734 | 2350.255  | 2070.157 | -700.124  |
| 2.0 °C_late mature rice    | -2840.214 | 14750.812 | -12510.515 | -2060.577 |

From Table 3, the precise equations are independently built using the change of Solar Radiation, Maximum Temperature, Minimum Temperature and Precipitation as independent variables. The change of rice yields are the dependent variables. It can be seen that the Maximum Temperature is the most important influencing factor for both early mature rice and late mature rice. The climate change impacts on rice under the 2.0 °C warming scenario is more obvious than the 1.5 °C warming scenario.

Equation (6) is used to calculate the PCC of early mature rice and late mature rice under both the 1.5 and 2.0 °C warming scenario. The results in Table 4 indicate that the precipitation is the main influencing factor of rice yield reduction for both early mature rice and late mature rice under the 1.5 °C warming scenario. Since the temperature and precipitation are all important factors influencing the rice yield, thus these climatic variables are influencing the rice yields in a combinatory way.

Table 4. Pearson Correlation Coefficient (PCC) of climatic variables and rice yields. Rice Yield (RY), Solar Radiation (SR), Maximum Temperature (TM), Minimum Temperature (TN) and Precipitation (P).

| Warming Scenario | RY  | SR  | TM  | TN  | P     |
|------------------|-----|-----|-----|-----|-------|
| 1.5 °C_early mature rice | 1   | 0.057  | 0.064 | 0.037 | -0.697 |
|                  | SR -0.327  | 1   | 0.997 | 0.997 | 0.108 |
|                  | TM -0.064  | 0.997 | 1   | 0.998 | 0.116 |
|                  | TN -0.037  | 0.997 | 0.998 | 1 | 0.124 |
|                  | P     | -0.697 | 0.108 | 0.116 | 0.124 |
| 1.5 °C_late mature rice | 1   | -0.327  | -0.315 | -0.318 | -0.718 |
|                  | SR -0.315  | 0.997 | 1   | 0.998 | 0.116 |
|                  | TM -0.318  | 0.997 | 0.998 | 1 | 0.124 |
|                  | TN     | -0.718 | 0.108 | 0.116 | 0.124 |
| 2.0 °C_early mature rice | 1   | 0.099  | 0.19  | 0.261 | -0.054 |
|                  | SR 0.099  | 1   | 0.865 | 0.399 | -0.225 |
|                  | TM 0.19   | 0.865 | 1   | 0.552 | -0.009 |
|                  | TN 0.261  | 0.399 | 0.552 | 1 | 0.276 |
|                  | P     | -0.054 | -0.225 | -0.009 | 0.276 |
| 2.0 °C_late mature rice | 1   | 0.287  | 0.283 | -0.262 | -0.318 |
|                  | SR 0.287  | 1   | 0.865 | 0.399 | -0.225 |
|                  | TM 0.283  | 0.865 | 1   | 0.552 | -0.009 |
|                  | TN -0.262 | 0.399 | 0.552 | 1 | 0.276 |
|                  | P     | -0.318 | -0.225 | -0.09  | 0.276 |

3.5. Adaptive Measures to Increase Rice Yields

3.5.1. Adjusting Planting Dates

The optimal planting dates for early mature and late mature rice are simulated according to the method introduced in Section 2.2.5. The designation Day of Year (DOY) is adopted to show the difference in planting dates at the sites. Figure 7a clearly shows that the simulated early mature yields increase with increasing planting dates at the beginning and then reach the maximum; however, the yields decrease with a further increase in planting dates. The results in Figure 7b show that the yields all decrease with the increase in planting dates. Therefore, the results indicate that the earlier planting dates would be better for late mature rice.
would likely be held constant or increase little when the use of fertilizer reached 240 kg/ha for early mature rice. As shown in Figure 8a, the yields would stagnate when the use of fertilizer reached near 240 kg/ha for early mature rice at most sites. Using Equation (4), the 240 kg/ha use of fertilizer would be the best choice for early mature rice. Figure 8b shows that the yields for most sites would likely be held constant or increase little when the use of fertilizer reached 240 kg/ha, which is similar to the results for early mature rice. Therefore, it can be concluded that 240 kg/ha of fertilizer would be the lowest usage to obtain the highest yields in the entire region.

Figure 7. Simulated changes in planting dates and the corresponding yields at each site: (a) Early mature rice and (b) late mature rice.

The numbers in parentheses are the optimized planting dates shown in form of DOY. The simulated planting dates of early mature rice are: CZ (93), GY (73), GZ (93), HY (93), HZ (103), LF (83), LZ (123), MX (93), QJ (108), XW (93), YJ (83), and ZS (78). The simulated planting dates for late mature rice are: CZ (208), GY (203), GZ (203), HY (203), HZ (203), LF (203), LZ (198), MX (188), QJ (193), XW (208), YJ (203), and ZS (203). To obtain the average operational level of this region, the optimized planting dates are averaged to obtain a planting date that would be representative of local management operations. The optimized planting dates for early mature rice and late mature rice for this region are 101 and 201, respectively.

3.5.2. Identifying the Optimal Usage of Fertilizers

Figure 8 clearly shows the relationship between the use of fertilizer and yields of all sites for the double cropping of rice. As shown in Figure 8a, the yields would stagnate when the use of fertilizer reached near 240 kg/ha for early mature rice at most sites. Using Equation (4), the 240 kg/ha use of fertilizer would be the best choice for early mature rice. Figure 8b shows that the yields for most sites would likely be held constant or increase little when the use of fertilizer reached 240 kg/ha, which is similar to the results for early mature rice. Therefore, it can be concluded that 240 kg/ha of fertilizer would be the lowest usage to obtain the highest yields in the entire region.

Figure 8. Simulated use of fertilizer and corresponding yields at each site for (a) early mature rice and (b) late mature rice.
4. Discussion

4.1. Climate Change Impacts on Rice Yields Under the 1.5 and 2.0 °C Warming Scenarios

The reduction in flowering and maturity durations shown in Figures 3 and 4 indicate that the flowering and maturity durations are shortened under both the 1.5 and 2.0 °C warming scenarios. The future climatic change means higher temperature, thus the GDD has reached a higher level compared with the normal level. Therefore, each stage of the rice growth is changing especially the flowering and maturity durations. This conclusion has been proven in the studies of others [74–76]. Also, the temperature under the 2.0 °C warming scenarios is higher than that under the 1.5 °C warming scenario. Consequently, the durations under the 2.0 °C warming scenario reduce more than those under the 1.5 °C warming scenario.

As shown in Figure 5, it can be obtained that the rice yields are reduced under the 1.5 and 2.0 °C warming scenarios. There are two main reasons for this: (1) The flowering and maturity durations are crucial to rice growth, and the high temperature will reduce the durations and further reduce the rice yields. Commonly, a 1.0 °C increase in temperature could cause yields to decline from 3 to 10% [45]. (2) The increased temperature would influence canopy photosynthesis, the accumulation of biomass and eventually the rice yields [77]. When the temperature gets higher, the rate of photosynthesis gets lower, and the rate of respiratory action gets higher (−10 °C −25 °C). The rate of photosynthesis gets higher as the temperature increases, and when the temperature gets near 25 °C, the rate of photosynthesis will reach the highest. Then, the rate of photosynthesis will decrease when the temperature continues to increase (higher than 25 °C). However, the rate of respiratory action will get higher when the temperature continues to increase (lower than 55 °C). Therefore, the mentioned two reasons are the main reason for the reduction of rice yields. The yields under the 2.0 °C warming scenario are reduced more than those under the 1.5 °C warming scenario. The reason is that the temperature under the 2.0 °C warming scenario is higher than that under the 1.5 °C warming scenario. Therefore, the durations under the 2.0 °C warming scenario are reduced more, and the rate of photosynthesis is less than that under the 1.5 °C warming scenario. Also, the rate of respiratory action under the 2.0 °C warming scenario is more than that under the 1.5 °C warming scenario.

Figure 6 shows that the yields of each site increase significantly compared with results without any consideration of CO2 fertilization. However, for most sites, the reduction is obvious, and there are only a few sites that can be equal to the baseline time. This is because rice is a C3 plant; it responds more sensitively to the effects of CO2 in photosynthetic carbon assimilation than other crops [78,79].

When the CO2 fertilization effects are considered, the yields under the 2.0 °C warming scenario still reduce more than those under the 1.5 °C warming scenario. This shows that the positive impacts from CO2 fertilization can hardly make up the total loss from climate change. The results obtained in this study have been proven in other similar simulations. Faye et al. simulated the impacts of climate change using the 2.0 °C increase in global warming, and the results show that there will be a reduction of 11% in yields in the West African Sudan Savanna [80]. Schleussner et al. explores the global crop productivity changes under the 1.5 and 2.0 °C scenarios, and finds out that the climate change will lead to more extreme low yields, in particular across tropical regions [81].

From Tables 3 and 4, it can be concluded that the Solar Radiation (SR) is in a positive relationship with the rice yields. SR is the positive influencing factor that supports rice growth, because it can provide energy from the sun [82]. The increase in precipitation is also a positive influencing factor that can help the growth of rice [26,53]. The increase in precipitation means abundant water; therefore, the rice yield could possibly grow well under this kind of environmental condition. Thus, both an increase in solar radiation and in precipitation are two positive climatic variables that support rice growth.
4.2. Optimal Management Practices to Increase Rice Yields

Adjusting the planting dates of rice is a useful method in facing the challenging of climate change that has been widely evaluated worldwide [76–78]. The average of planting dates in this region is optimized to change the phenology, and thus further increase rice yields.

The adjustment of the planting dates will change the growing climatic information during the rice growth [79]. The adjusted planting dates involve different climatic information for rice growth, especially the temperature. The adjusted planting dates will help to avoid the high temperature, which will prolong the flowering and maturity durations [80].

According to the actual usage of fertilizer at all sites, the present average usage of fertilizer for the entire region is approximately 240 kg/ha. According to the results shown in Figure 8, it can be noted that the usage of fertilizer has not reached the optimized usage. Therefore, the usage of fertilizer should be increased. From Figure 8a, it can be obtained that the yields are all increasing when the use of fertilizer is increasing. This is because the yields at all sites have not reached their yield potential. In other words, the use of fertilizer is a very important influencing factor that will impact the yields profoundly. From Figure 8b, it can be seen that the yields are not increasing obviously at the LZ and CZ sites. This is because the use of fertilizer is not the main influencing factor at these two sites. In other words, the yields may have reached near the yield potential, of which the main influencing factors are all climatic-related variables. The use of fertilizer will contribute a little to the increase of yield; thus, the yield will not increase significantly, even though the use of fertilizer increases. Since the use of fertilizers is confirmed for both early mature rice and late mature rice in this region, the consideration of environmental protection will also be reminded. It is recommended that fertilizer usage should be balanced between industrial fertilizer and organic matter to protect the environment and maintain a low concentration of CO2. The results from this study are consistent with the results from similar research [81–84].

5. Conclusions

In this study, the potential impacts of climate change upon rice growth and rice yields are assessed under the 1.5 and 2.0 °C warming scenarios (2106–2115) at 12 sites in the PRD, China. The flowering and maturity duration are shortened, and the yield will be reduced by 292.5 kg/ha (558.9 kg/ha) for early mature rice under the 1.5 °C (2.0 °C) warming scenarios. Similarly, the yields will reduce by 151.8 kg/ha (380.0 kg/ha) for early mature rice under the 1.5 °C (2.0 °C) warming scenarios. The main reasons for the yield reduction are the temperature-induced shortened flowering and maturity durations, and the temperature-induced decreasing rate of photosynthesis and increasing rate of respiratory action. The negative impacts of climate change would be eliminated if the planting dates are delayed by eight days for early mature rice, and advanced 15 days for late mature rice. The simulated optimal usage of fertilizer is 240 kg/ha for both early mature rice and late mature rice. All simulations suggest adopting an increased use of industrial fertilizer and organic matter, and to balance the usage scientifically. Although this study has its limitations, the results provide useful advice for improving rice growth and management practices to better cope with the potential challenge of climate change.

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Appendix A

**Table A1.** Detailed information of the soil of each site.

| Site | Color | Drainage   | Runoff           | Clay (%) | Organic (%) | pH  | Exchange (cmol/kg) | Nitrogen (%) |
|------|-------|------------|------------------|----------|-------------|-----|--------------------|--------------|
| MX   | Brown | Well       | Moderately High  | 34.2     | 1.79        | 4.9 | 2.4                | 0.16         |
| GY   | Yellow| Moderately Well | Moderately High | 18.4     | 1.4         | 5   | 3.1                | 2.11         |
| GZ   | Red   | Moderately Well | Moderately High | 14       | 3.46        | 7.1 | 1                  | 0.18         |
| SG   | Red   | Moderately Well | Moderately High | 21.5     | 1.61        | 7.3 | 2.3                | 0.1          |
| LZ   | Brown | Well       | Moderately High  | 32.9     | 3.3         | 8.1 | 3.4                | -99          |
| XW   | Red   | Moderately Well | Moderately High | 20.1     | 2.21        | 5.8 | 0.1                | 0.12         |
| CZ   | Red   | Moderately Well | Moderately High | 35       | 2.43        | 7.5 | 1                  | 0.11         |
| YJ   | Red   | Well       | Moderately High  | 14.2     | 2.06        | 4.8 | 1.1                | 0.12         |
| HY   | Yellow| Moderately Well | Moderately High | 14       | 1.99        | 4.9 | 1.3                | 0.09         |
| HZ   | Red   | Moderately Well | Moderately High | 6.7      | 0.89        | 5   | 0.7                | 0.06         |
| LF   | Red   | Moderately Well | Moderately High | 11.5     | 2.51        | 5   | 2.5                | 0.13         |
| ZS   | Red   | Well       | Moderately High  | 14.2     | 2.06        | 4.8 | 1.1                | 0.12         |
Table A2. Detailed information of the management of each site.

| Site | Cropping | Cultivar                  | Planting | Emergence | Tillering | Jointing | Booting | Heading | Maturing | Urea (kg) | Compound (kg) |
|------|----------|---------------------------|----------|-----------|-----------|----------|---------|---------|----------|-----------|----------------|
| CZ   | Early mature | Teyou254                | 2/18     | 2/22      | 4/2       | 5/8      | 5/30    | 6/10    | 7/11     | 25.5      | 60              |
|      | Late mature  | Xieyou3550              | 7/18     | 7/22      | 8/14      | 9/10     | 9/22    | 10/2    | 11/10    | 27        | 60              |
| GY   | Early mature | Xuehuanian               | 3/7      | 3/12      | 4/20      | 5/18     | 6/4     | 6/14    | 7/9      | 10        | 50              |
|      | Late mature  | Xuehuanian               | 7/6      | 7/10      | 8/18      | 9/6      | 9/16    | 9/30    | 11/4     | 5         | 45              |
| HY   | Early mature | Zayou                   | 3/23     | 3/27      | 5/6       | 5/26     | 6/10    | 6/20    | 7/18     | 1.5       | 35              |
|      | Late mature  | Zayou                   | 7/11     | 7/15      | 8/18      | 9/4      | 9/14    | 9/24    | 10/26    | 42.5      |                |
| HZ   | Early mature | Qishanzhan              | 3/28     | 3/31      | 5/2       | 5/26     | 6/12    | 6/19    | 7/18     | 15        | 85              |
|      | Late mature  | Gaoyoubaigu             | 7/16     | 7/19      | 8/16      | 9/8      | 9/24    | 10/3    | 10/31    | 50        | 20              |
| LZ   | Early mature | Jinyou207               | 3/27     | 3/29      | 5/3       | 5/25     | 6/15    | 6/22    | 7/18     | 40        | 20              |
|      | Late mature  | Jinyou253               | 7/5      | 7/7       | 7/29      | 8/21     | 9/14    | 9/20    | 10/25    | 50        | 20              |
| LF   | Early mature | You1402                 | 3/12     | 3/19      | 4/20      | 5/27     | 6/17    | 6/22    | 7/28     | 20        | 30              |
|      | Late mature  | Yueyou350               | 7/22     | 7/24      | 8/20      | 9/2      | 9/23    | 10/6    | 11/7     | 10        | 30              |
| MX   | Early mature | Meiyou6                 | 3/8      | 3/10      | 4/24      | 5/18     | 5/28    | 6/4     | 7/8      | 30.5      | 18              |
|      | Late mature  | Meiyou6                 | 7/17     | 7/19      | 8/14      | 9/8      | 9/18    | 9/26    | 11/4     | 34        | 16              |
| QJ   | Early mature | Jufengnian              | 3/7      | 3/10      | 4/27      | 5/16     | 6/3     | 6/11    | 7/11     | 16        | 30              |
|      | Late mature  | Baikenian               | 7/7      | 7/11      | 8/4       | 8/22     | 9/14    | 9/20    | 10/20    | 15        | 45              |
| GZ   | Early mature | Meixiangzhan            | 3/20     | 3/23      | 5/3       | 5/25     | 6/6     | 6/15    | 7/13     | 20        | 25              |
|      | Late mature  | Tashan25                | 7/23     | 7/26      | 8/26      | 9/10     | 9/24    | 10/3    | 11/3     | 25        | 27.5            |
| XW   | Early mature | Gaokang999              | 2/26     | 3/2       | 4/24      | 5/10     | 5/30    | 6/7     | 7/6      | 35        |                |
|      | Late mature  | Boyou15                 | 7/19     | 7/22      | 8/28      | 9/20     | 10/4    | 10/12   | 11/10    | 10        | 25              |
| YJ   | Early mature | Zayou                   | 3/21     | 3/24      | 5/3       | 6/2      | 6/14    | 6/23    | 7/19     | 35        | 12              |
|      | Late mature  | Zayou                   | 7/21     | 7/23      | 8/20      | 9/21     | 9/29    | 10/7    | 11/8     | 45        | 30              |
| ZS   | Early mature | Tainanzhan              | 2/21     | 2/27      | 4/23      | 5/14     | 6/1     | 6/11    | 7/3      | 22        |                 |
|      | Late mature  | Tainanzhan              | 7/14     | 7/16      | 8/12      | 9/8      | 9/16    | 9/23    | 10/14    | 50        |                 |
Table A3. The detail of the site, cropping system, rice cultivar name and parameters.

| Site | Latitude | Longitude | Cropping | Cultivar         | P1   | P2R   | P5   | P2O  | G1   | G2   | G3   | G4   |
|------|----------|-----------|----------|------------------|------|-------|------|------|------|------|------|------|
| CZ   | 23.4     | 116.42    | Early    | Teyou254         | 500.0| 200.0 | 400.0| 12.1 | 100.0| 0.0270| 0.11 | 1.00 |
|      |          |           | mature   | Xieyou3550       | 550.0| 250.0 | 400.0| 12.2 | 120.0| 0.0270| 0.11 | 1.00 |
| GY   | 23.02    | 112.27    | Early    | Xuehuanian       | 200.0| 400.0 | 400.0| 11.2 | 300.0| 0.0220| 1.00 | 1.00 |
|      |          |           | mature   | Xuehuanian       | 210.0| 410.0 | 400.0| 11.3 | 300.0| 0.0220| 1.00 | 1.00 |
| HY   | 23.48    | 114.44    | Early    | Zayou254         | 400.0| 400.0 | 600.0| 11.1 | 300.0| 0.0110| 0.55 | 1.00 |
|      |          |           | mature   | Zayou254         | 400.0| 400.0 | 500.0| 11.2 | 300.0| 0.0110| 0.55 | 1.00 |
| HZ   | 21.39    | 110.37    | Early    | Qishanzhan       | 400.0| 300.0 | 400.0| 12.1 | 200.0| 0.0240| 0.44 | 1.00 |
|      |          |           | mature   | Gaozhoubai 50    | 410.0| 320.0 | 400.0| 12.1 | 200.0| 0.0240| 0.44 | 1.00 |
| LZ   | 24.48    | 112.22    | Early    | Jinyou207        | 100.0| 300.0 | 500.0| 12.2 | 500.0| 0.0220| 1.00 | 1.00 |
|      |          |           | mature   | Jinyou253        | 110.0| 320.0 | 310.0| 12.2 | 500.0| 0.0220| 1.00 | 1.00 |
| LF   | 22.87    | 115.39    | Early    | You1402          | 100.0| 300.0 | 300.0| 12.1 | 100.0| 0.0270| 0.11 | 1.00 |
|      |          |           | mature   | Yueyou350        | 300.0| 300.0 | 500.0| 12.3 | 300.0| 0.0270| 0.11 | 1.00 |
| MX   | 24.17    | 116.04    | Early    | Meiyou6          | 120.0| 300.0 | 580.0| 12.2 | 500.0| 0.0220| 1.00 | 1.00 |
|      |          |           | mature   | Meiyou6          | 400.0| 400.0 | 500.0| 12.2 | 500.0| 0.0220| 1.00 | 1.00 |
| QJ   | 24.4     | 113.36    | Early    | Jufengnian       | 200.0| 200.0 | 350.0| 12.1 | 350.0| 0.0230| 1.00 | 1.00 |
|      |          |           | mature   | Baikenian        | 300.0| 300.0 | 500.0| 12.2 | 500.0| 0.0220| 0.66 | 1.00 |
| GZ   | 23.13    | 113.29    | Early    | Meixiangzhan     | 100.0| 300.0 | 500.0| 12.3 | 100.0| 0.0270| 0.11 | 1.00 |
|      |          |           | mature   | Teshan25         | 120.0| 320.0 | 500.0| 12.3 | 100.0| 0.0280| 0.11 | 1.00 |
| XW   | 20.2     | 110.11    | Early    | Gaokang999       | 300.0| 200.0 | 350.0| 12.1 | 350.0| 0.0230| 1.00 | 1.00 |
|      |          |           | mature   | Boyou15          | 310.0| 220.0 | 350.0| 12.1 | 350.0| 0.0230| 1.00 | 1.00 |
| YJ   | 21.5     | 111.58    | Early    | Zayou254         | 400.0| 200.0 | 350.0| 12.1 | 350.0| 0.0350| 0.26 | 1.00 |
|      |          |           | mature   | Zayou254         | 400.0| 200.0 | 350.0| 12.1 | 350.0| 0.0350| 0.26 | 1.00 |
| ZS   | 22.3     | 113.24    | Early    | Tainanzhan       | 500.0| 200.0 | 350.0| 13.8 | 300.0| 0.025 | 1.00 | 1.00 |
|      |          |           | mature   | Tainanzhan       | 220.0| 240.0 | 700.0| 12.1 | 310.0| 0.035 | 0.26 | 1.00 |
Table A4. Climate patterns under historic conditions. The rows are ordered from January to December.

| Site | CZ | GY | GZ | HY | HZ | LF | LZ | MX | SG | XW | YJ | ZS |
|------|----|----|----|----|----|----|----|----|----|----|----|----|
| R    | 11.9| 9.9| 10.4| 11.3| 10.4| 12.0| 8.6| 11.1| 9.2| 11.1| 12.0| 10.8|
| TM   | 18.8| 17.2| 18.6| 18.9| 19.9| 19.3| 13.7| 17.1| 15.6| 21.2| 19.4| 18.0|
| TN   | 11.0| 9.7| 10.7| 10.5| 13.3| 12.1| 6.0| 7.6| 7.5| 15.1| 12.1| 11.6|
| P    | 6.2 | 8.2| 6.4 | 5.2 | 7.5 | 7.2 | 10.9| 4.6 | 8.3 | 10.2| 4.5 | 6.1 |

Note: The table continues with similar data for other sites and months.
Table A5. Climate patterns under the 1.5 °C warming scenario.

| Site | CZ | GY | GZ | HY | HZ | LF | LZ | MX | SG | XW | YJ | ZS |
|------|----|----|----|----|----|----|----|----|----|----|----|----|
| R    | 13.0| 11.0| 11.6| 12.4| 12.1| 13.4| 9.8 | 12.2| 10.4| 13.2| 13.4| 12.4|
| TM   | 18.9| 17.5| 18.8| 19.0| 20.2| 19.4| 14.0| 17.3| 15.9| 21.7| 19.5| 18.2|
| TN   | 10.9| 9.7 | 10.8| 10.3| 13.5| 12.0| 6.1 | 7.5 | 7.5 | 15.3| 11.9| 11.6|
| F    | 7.6 | 6.7 | 5.3 | 7.3 | 7.2 | 7.4 | 9.1 | 7.0 | 6.7 | 9.3 | 6.6 | 6.5|

Site: CZ, GY, GZ, HY, HZ, LF, LZ, MX, SG, XW, YJ, ZS

Note: The values represent specific climate metrics for each site under the 1.5 °C warming scenario.
Table A6. Climate patterns under the 2.0 °C warming scenario.

| Site | CZ  | GY  | GZ  | HY  | HZ  | LF  | LZ  | MX  | SG  | XW  | YJ  | ZS  |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| R    | 12.8| 10.5| 11.1| 12.2| 11.7| 13.0| 9.2 | 12.0| 9.8 | 12.6| 13.0| 11.9|
| TM   | 19.2| 17.6| 19.0| 19.1| 20.5| 19.7| 14.1| 17.5| 16.0| 21.8| 19.8| 18.4|
| TN   | 11.1| 9.8 | 10.9| 10.5| 13.7| 12.2| 6.1 | 7.7 | 7.6 | 15.5| 12.2| 11.9|
| P    | 6.4 | 6.6 | 5.6 | 5.4 | 5.9 | 5.2 | 8.4 | 6.1 | 6.8 | 7.2 | 4.3 | 5.2 |

20.2 ± 1.0
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