atmosphere

MDPI

Article

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

Yahui Guo [1,2,3], Wenxiang Wu [1,3,*], Mingzhu Du [4], Xiaoxuan Liu [5,6], Jingzhe Wang [7] and Christopher Robin Bryant [8,9]

1 Academician workstation of Zhai Mingguo, University of Sanya, Sanya 572000, China; guoyh@lreis.ac.cn
2 Beijing Key Laboratory of Urban Hydrological Cycle and Sponge City Technology, College of Water Sciences, Beijing Normal University, Beijing 100875, China
3 Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
4 Agricultural Information Institute, Chinese Academy of Agricultural Sciences, Beijing 100081, China; dumingzhu@126.com
5 Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing 100084, China; liuxx16@mails.tsinghua.edu.cn
6 Joint Center for Global Change Studies, Beijing 100875, China
7 Guangdong Key Laboratory of Integrated Agro-environmental Pollution Control and Management, Guangdong Institute of Eco-environmental Science & Technology, Guangzhou 510650, China; jingzhecb@gmail.com
8 School of Environmental Design and Rural Development, University of Guelph, Guelph, ON N1G2W5, Canada; christopher.robin.bryant@gmail.com
9 Géographie, Université de Montréal, Montréa, QC H2V2B8, Canada
* Correspondence: wuwenxiang2018@163.com

Received: 11 July 2019; Accepted: 19 September 2019; Published: 21 September 2019

check for updates

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; CO_2 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 CO_2 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 (Gaozhoubaigu), LZ (Jinyou253), LF (Yueyou350), MX(Meiyou6), QJ (Baikenian), GZ (Teshan25), XW (Boyou15), YJ (Zayou) and ZS (Tainanzhan).

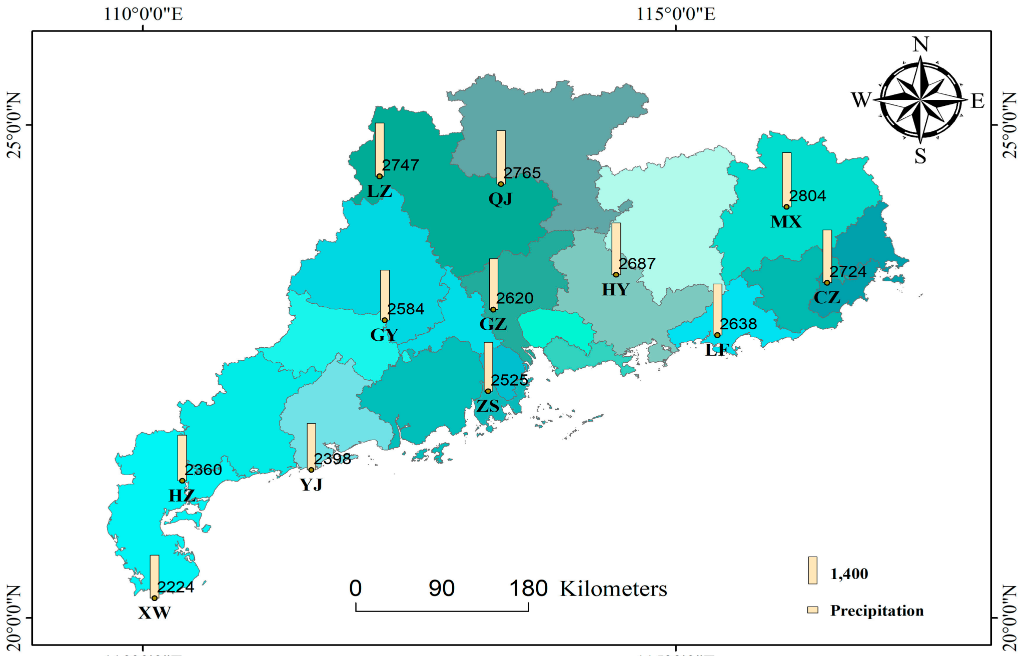

Figure 1. The study area, site locations and average annual precipitation (mm) from 1980–2010 are all indicated by histogram. The 'words' are the abbreviated names of sites, and the numbers indicate the average annual precipitation (mm).

2.2. Ceres-Rice Model

2.2.1. Model Description

The Decision Support System for Agro-technology Transfer (DSSAT) is the program that is developed by G. Hoogenboom, and J.W. Jones [37,38]. The program comprises crop simulation models for more than 42 crops. The Ceres-Rice Model simulates the growth, development and yield as a function of the soil-plant-atmosphere dynamics [39]. The model is a process-based model that is inbuilt in DSSAT, and it has been adopted to simulate the process of agricultural growth and yields for decades [40–43]. This model can evaluate crop yields based on management operation records, soil data, climate data and cultivar genetic coefficients. These cultivar genetic coefficients are actually a set of parameters that control the natural development of crops, such as flowering and maturing [44]. To be more specific, each cultivar genetic coefficient controls some aspects of the growth and development of the crop within the model. There are eight genetic coefficients for rice defined in the Ceres-Rice Model, namely: P1, P20, P2R, P5, G1, G2, G3 and G4 [31,45]. The model is able to capture spatial and temporal variations through thousands of reproduced Genotype × Environment × Management (G × E × M) interactions [46]. The model aims to simulate crop growth, development and yields, according to various levels of climate and genetic variations [47]. In the Ceres-Rice Model, the Growing Degree Days (GDD) is an important indicator, which controls the development stages [48]. When the GDD is accumulated to a certain value, the crop would be juvenile, floral, heading, flowering, grain filling, mature and harvested [49]. Therefore, the GDD is crucial to both the growth and yields of the crop. The GDD is calculated by a judgement of a function that is described in the following equation [50]:

$$\mathrm{GDD} = \begin{cases} T - T_{\mathrm{base}} \text{ for } T_{\mathrm{base}} < T < T_{\mathrm{opt}} \\ T_{\mathrm{high}} - T \text{ for } T_{\mathrm{opt}} < T < T_{\mathrm{high}} \\ 0 \quad \text{for } T < T_{\mathrm{base}} \text{ or } T > T_{\mathrm{high}} \end{cases}. \tag{1}$$

In the equation, T_{base}, T_{high} and T_{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	Atmosphere 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:

$$\text{NRMSE} = \frac{1}{\overline{O_i}} \sqrt{\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n}} \tag{2}$$

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 $\overline{O_i}$ 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 CO_2 fertilization effect will influence the yield profoundly; to some extent, the higher the CO_2 concentration, the higher the yield will be [26]. In order to assess the CO_2 fertilization effect, the simulation is also completed by using the present and future potential concentrations of CO_2. To assess the CO_2 fertilization effect, the future CO_2 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 CO_2 fertilization effect. The comparison is defined in the following equation:

$$Y_c = Y_a - Y_b \tag{3}$$

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:

$$\Delta\varphi = \left|\frac{\Delta_{yield}}{\Delta_{fertilizer}}\right| \tag{4}$$

In the equation, Δ_{yield} and $\Delta_{fertilizer}$ represent the change of yield and the change of fertilizer, respectively. When $\Delta\varphi$ 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]:

$$\text{yield} = \text{a} * \text{R} + \text{b} * \text{TM} + \text{c} * \text{TN} + \text{d} * \text{P} + \Delta \tag{5}$$

In the equation, yield represents the reduced rice yield; R represents the average of daily solar radiation; TM represents the highest daily average temperature, TN represents the lowest daily average temperature; P represents the precipitation and Δ 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 combinatory 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:

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

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.

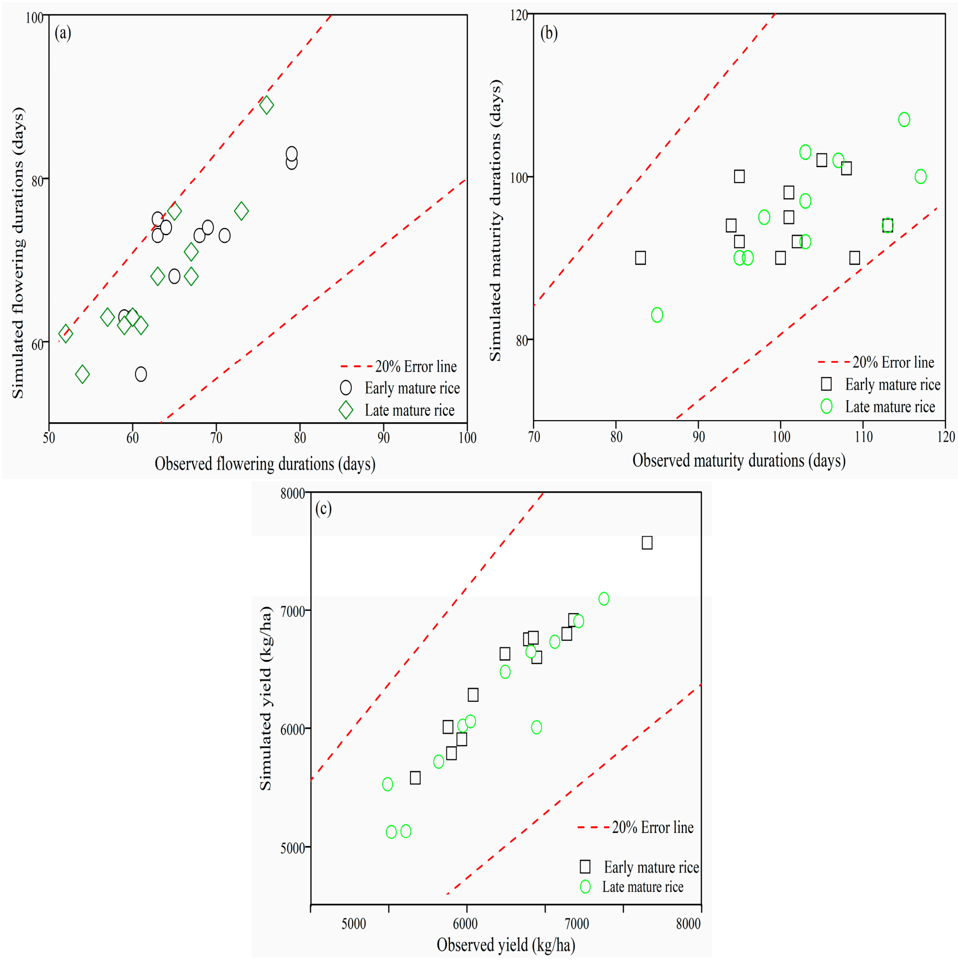

Figure 2. The calculated Normalized Root Mean Square Errors (NRMSEs) for early mature rice and late mature rice, respectively.

3.2. Changes in Climatic Variables Under the 1.5 and 2.0 °C Warming Scenarios

The temperature, precipitation, solar radiation and projected CO_2 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, 0.21 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 [1].

Warming Scenario	$\overline{TM}$ (°C)	$\overline{TN}$ (°C)	$\overline{P}$ (mm)	$\overline{R}$ (h)	CO_2 (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] $\overline{TM}$, $\overline{TN}$, $\overline{P}$, and $\overline{R}$ 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 °C (2.0 °C) warming scenarios. Since the 1.5 and 2.0 °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 °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 °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 °C warming scenarios, respectively. It can be concluded that climate change under the 2.0 °C warming scenario reduces more days than do the flowering durations under the 1.5 °C warming scenario. In other words, the potential impacts from climate change on the flowering durations under the 2.0 °C warming scenario would lead to a more obvious reduction of the flowering durations than under the 1.5 °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 °C warming scenario. Similarly, the maturity durations of early mature rice decreased 4.4 to 11.8 days under the 2.0 °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 °C warming scenarios, respectively. The maturity durations of late mature rice decreased from 0.6 to 33.0 days under the 1.5 °C warming scenario and from 1.4 to 40.6 days under the 2.0 °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 °C warming scenarios, respectively.

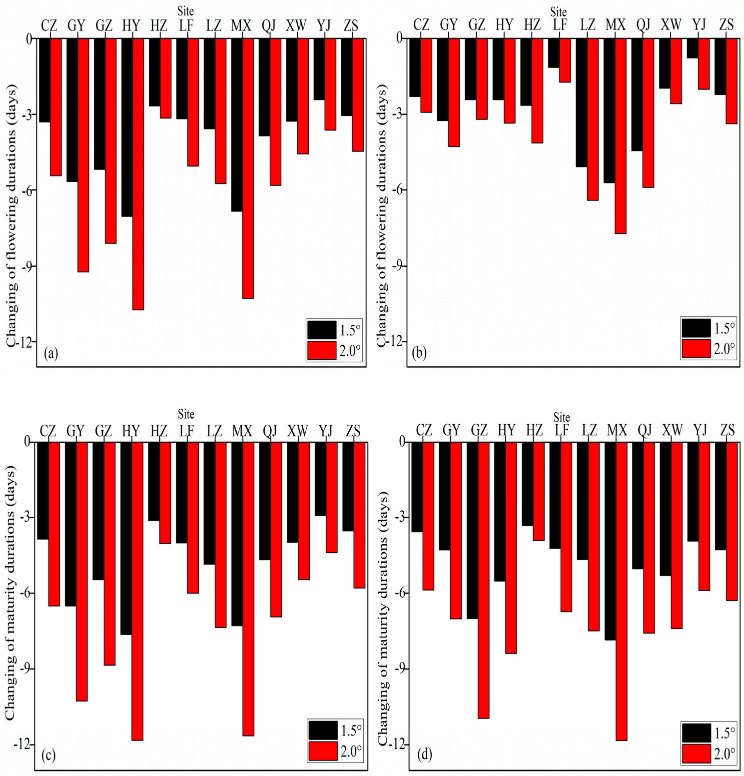

Figure 3. Changes in the flowering durations and maturity durations under the 1.5 and 2.0 °C warming scenarios relative to the baseline time for (**a**,**c**) early mature rice and (**b**,**d**) late mature rice.

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.

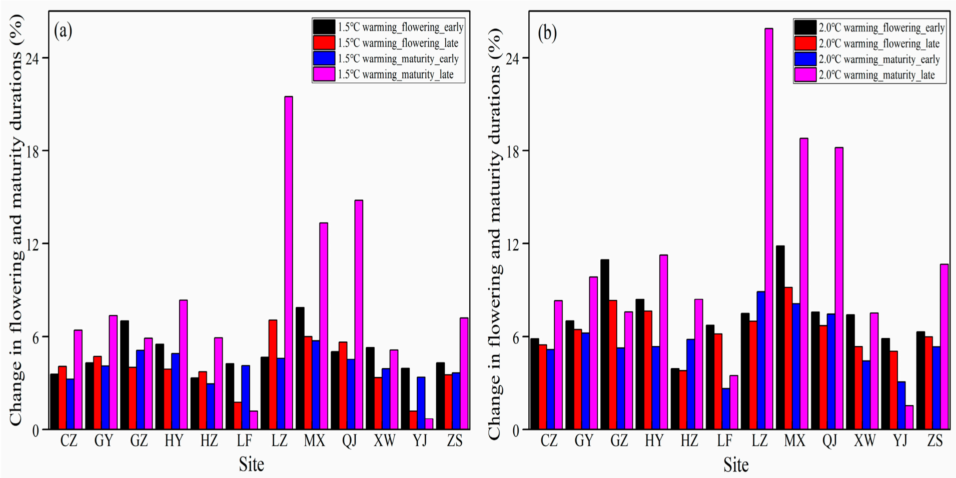

Figure 4. Change in flowering and maturity durations under the 1.5 and 2.0 °C warming scenarios relative to the baseline time, respectively. Note: (**a**) Under the 1.5 °C warming scenario and (**b**) under the 2.0 °C warming scenario.

3.4. Impacts of Climate Change on Rice Yields

3.4.1. Impacts of Climate Change on Rice Yields without the CO_2 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.

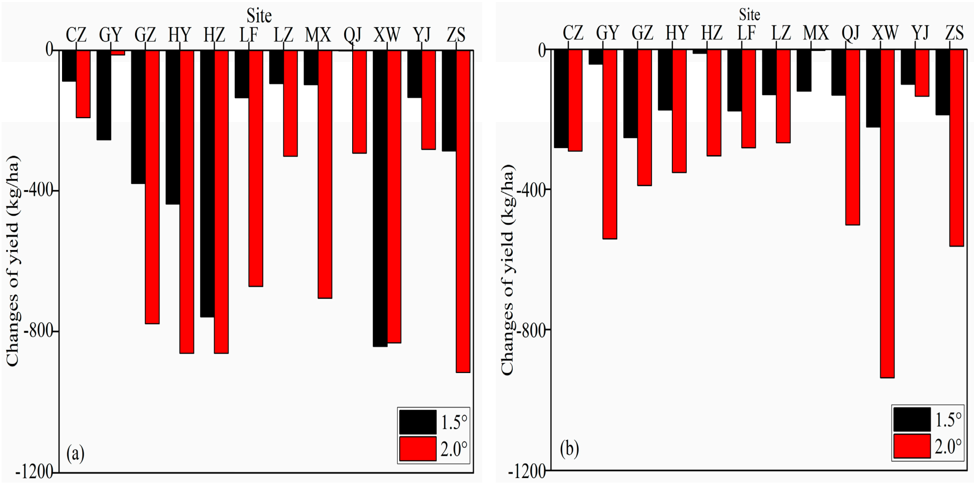

Figure 5. Changes of yields under the 1.5 and 2.0 °C warming scenarios relative to the baseline time for (**a**) early mature rice and (**b**) late mature rice.

3.4.2. Impacts of CO_2 Fertilization on Rice Yields

When the CO_2 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.

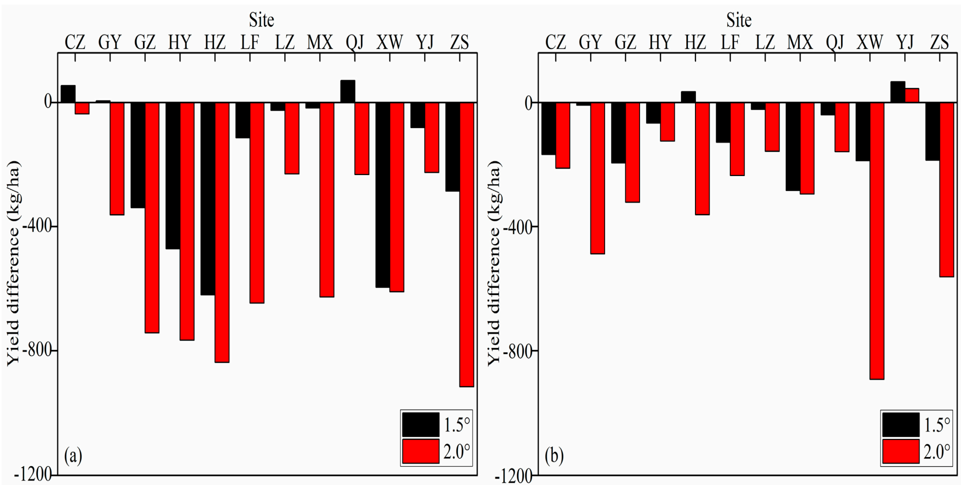

Figure 6. Changes in yields under the 1.5 and 2.0 °C warming scenarios with the CO_2 fertilization effect relative to the baseline period for the temperature. Note (**a**) for early mature rice and (**b**) for late mature rice.

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.

Names	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	PCC	RY	SR	TM	TN	P
1.5 °C_early mature rice	RY	1	0.057	0.064	0.037	−0.697
	SR	0.057	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
1.5 °C_late mature rice	RY	1	−0.327	−0.315	−0.318	−0.718
	SR	−0.327	1	0.997	0.997	0.108
	TM	−0.315	0.997	1	0.998	0.116
	TN	−0.318	0.997	0.998	1	0.124
	P	−0.718	0.108	0.116	0.124	1
2.0 °C_early mature rice	RY	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	1
2.0 °C_late mature rice	RY	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	1

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.

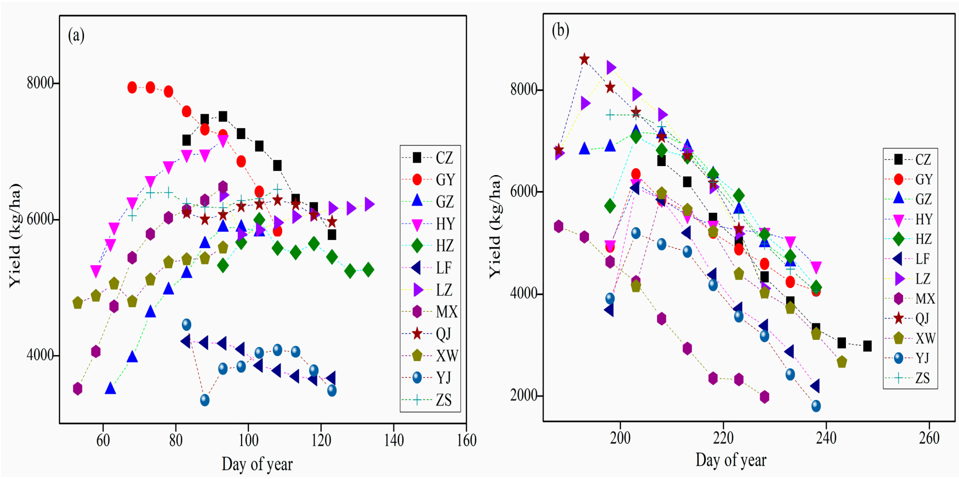

Figure 7. Simulated changes in planting dates and the corresponding yields at each site: (**a**) Early mature rice and (**b**) late mature rice.

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 stimulated 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.

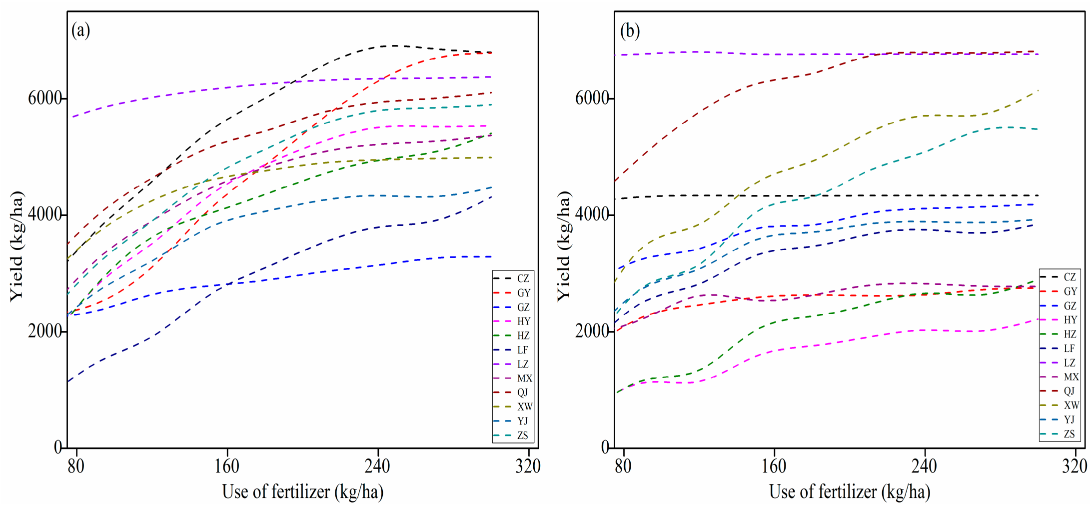

Figure 8. Simulated use of fertilizer and corresponding yields at each site for (**a**) early mature rice and (**b**) late mature rice.

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 CO_2. 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.

Author Contributions: Each of the authors contributed substantially to this work in the following ways: Conceptualization, Y.G.; Data curation, M.D.; Formal analysis, Y.G.; Funding acquisition, W.W.; Investigation, Y.G.; Methodology, Y.G.; Resources, X.L.; Software, Y.G.; Validation, J.W.; Writing–original draft, Y.G.; Writing–review & editing, Y.G., W.W. and C.R.B.

Funding: This research is funded by the National Key Research and Development Program of China (2016YFA0602402) and the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA19040101, XDA19040304).

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

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

Sit	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	Gaozhoubaigu	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	50
LF	Early mature	YouI402	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	Teshan25	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 mature	Teyou254	500.0	200.0	400.0	12.1	100.0	0.0270	0.11	1.00
			Late mature	Xieyou3550	550.0	250.0	400.0	12.2	120.0	0.0270	0.11	1.00
GY	23.02	112.27	Early mature	Xuehuanian	200.0	400.0	400.0	11.2	300.0	0.0220	1.00	1.00
			Late mature	Xuehuanian	210.0	410.0	400.0	11.3	300.0	0.0220	1.00	1.00
HY	23.48	114.44	Early mature	Zayou	400.0	400.0	600.0	11.1	300.0	0.0110	0.55	1.00
			Late mature	Zayou	400.0	400.0	500.0	11.2	300.0	0.0110	0.55	1.00
HZ	21.39	110.37	Early mature	Qishanzhan	400.0	300.0	400.0	12.1	200.0	0.0240	0.44	1.00
			Late mature	Gaozhoubaigu	410.0	320.0	400.0	12.1	200.0	0.0240	0.44	1.00
LZ	24.48	112.22	Early mature	Jinyou207	100.0	300.0	500.0	12.2	500.0	0.0220	1.00	1.00
			Late mature	Jinyou253	110.0	320.0	310.0	12.2	500.0	0.0220	1.00	1.00
LF	22.87	115.39	Early mature	YouI402	100.0	300.0	300.0	12.1	100.0	0.0270	0.11	1.00
			Late mature	Yueyou350	300.0	300.0	500.0	12.3	300.0	0.0270	0.11	1.00
MX	24.17	116.04	Early mature	Meiyou6	120.0	300.0	580.0	12.2	500.0	0.0220	1.00	1.00
			Late mature	Meiyou6	400.0	400.0	500.0	12.2	500.0	0.0220	1.00	1.00
QJ	24.4	113.36	Early mature	Jufengnian	200.0	200.0	350.0	12.1	350.0	0.0230	1.00	1.00
			Late mature	Baikenian	300.0	300.0	500.0	12.2	500.0	0.0220	0.66	1.00
GZ	23.13	113.29	Early mature	Meixiangzhan	100.0	300.0	500.0	12.3	100.0	0.0270	0.11	1.00
			Late mature	Teshan25	120.0	320.0	500.0	12.3	100.0	0.0280	0.11	1.00
XW	20.2	110.11	Early mature	Gaokang999	300.0	200.0	350.	12.1	350.0	0.0230	1.00	1.00
			Late mature	Boyou15	310.0	220.0	350.0	12.1	350.0	0.0230	1.00	1.00
YJ	21.5	111.58	Early mature	Zayou	100.0	200.0	350.0	12.1	310.0	0.0350	0.26	1.00
			Late mature	Zayou	400.0	200.0	350.0	12.1	350.0	0.0350	1.00	1.00
ZS	22.3	113.24	Early mature	Tainanzhan	500.0	200.0	350.0	13.8	300.0	0.025	1.00	1.00
			Late 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
	11.9	9.9	10.4	11.3	10.4	12.0	8.6	11.1	9.2	11.1	12.0	10.8
	9.8	8.2	8.6	9.1	9.7	10.4	7.1	8.8	7.4	11.9	10.3	9.4
	11.4	10.1	10.1	10.5	12.1	11.8	8.9	10.0	8.8	14.5	11.7	10.2
	12.6	11.6	11.6	12.0	14.0	13.7	10.1	11.4	10.2	17.6	13.7	12.7
	16.5	15.6	15.8	16.2	18.6	17.6	14.0	15.7	14.3	20.9	17.5	17.9
$\overline{R}$	16.3	16.4	16.4	16.2	18.6	18.2	14.8	15.6	15.1	21.4	18.1	18.1
	17.3	16.7	16.7	16.9	16.8	19.0	15.7	17.1	15.9	20.1	19.0	17.9
	16.8	15.7	15.9	16.4	16.3	18.7	14.9	16.6	15.0	18.8	18.6	16.9
	15.3	14.3	14.7	15.1	15.3	16.7	13.4	14.9	13.5	15.8	16.5	15.1
	14.7	14.5	14.8	14.7	14.6	16.1	13.3	14.2	13.8	15.0	15.9	14.4
	14.4	14.4	14.5	14.7	14.9	15.2	13.4	14.1	13.8	14.6	15.1	14.6
	12.8	12.3	12.5	12.8	12.5	13.3	11.2	12.6	11.7	12.6	13.3	12.5
	18.8	17.2	18.6	18.9	19.9	19.3	13.7	17.1	15.6	21.2	19.4	18.0
	19.0	17.5	18.9	19.1	20.2	19.6	14.3	17.6	16.1	22.8	19.9	18.3
	21.5	20.4	21.6	22.0	23.1	22.1	17.3	20.6	19.0	26.2	22.7	21.1
	24.7	24.0	25.1	25.4	26.6	25.0	21.6	24.1	23.0	29.7	25.9	24.7
	28.7	29.3	30.4	30.0	31.9	28.8	27.3	28.4	28.6	33.4	30.1	29.2
$\overline{TM}$	30.8	31.4	32.3	30.0	33.4	30.7	29.8	30.5	31.2	34.7	31.9	31.2
	31.8	31.9	32.7	32.2	33.3	31.3	30.6	31.5	32.0	34.3	32.7	31.8
	31.9	31.5	32.3	32.2	32.7	31.6	30.0	31.4	31.5	33.4	32.8	31.6
	30.9	30.2	31.2	31.1	31.5	30.9	28.3	30.0	29.9	31.7	31.5	30.4
	28.5	27.9	29.1	28.8	29.2	28.8	25.5	27.4	27.3	29.5	29.0	27.8
	25.4	24.2	25.4	25.4	26.6	25.8	21.5	24.1	23.2	26.9	25.5	24.6
	21.1	19.9	21.2	21.3	22.4	21.7	16.9	19.7	18.6	23.1	21.6	20.4
	11.0	9.7	10.7	10.5	13.3	12.1	6.0	7.6	7.5	15.1	12.1	11.6
	12.7	11.6	12.7	12.5	14.8	13.7	8.0	10.0	9.6	16.2	13.6	12.9
	15.2	14.2	15.4	15.3	17.6	16.2	10.8	13.0	12.4	19.3	16.3	16.1
	18.5	17.7	18.9	18.7	20.9	19.3	14.7	16.6	16.4	22.3	19.3	19.6
	22.4	22.0	23.2	22.7	25.2	22.9	19.4	20.3	21.0	25.4	22.9	23.5
$\overline{TN}$	25.1	24.7	25.8	25.4	26.7	25.5	22.6	23.2	24.1	26.5	25.5	25.7
	25.8	25.1	26.2	25.8	26.6	26.0	23.3	24.0	24.7	26.5	26.0	26.2
	25.4	24.3	25.4	25.3	25.9	25.7	22.4	23.4	23.7	25.8	25.5	25.7
	24.5	23.3	24.5	24.5	25.0	25.1	20.9	22.3	22.4	25.4	25.0	24.8
	21.2	19.7	21.0	21.1	22.4	22.2	16.7	18.3	18.2	23.6	22.0	22.3
	16.5	14.3	15.7	15.8	18.4	17.5	10.8	12.9	12.3	20.2	17.4	17.9
	12.3	10.6	11.9	11.7	14.8	13.5	7.0	8.6	8.4	16.7	13.5	13.5
	6.2	8.2	6.4	5.2	7.5	7.2	10.9	4.6	8.3	10.2	4.5	6.1
	16.7	18.1	17.7	16.9	17.3	16.5	18.6	17.6	18.6	14.6	16.4	16.4
	17.8	18.9	18.9	18.9	16.3	18.2	21.3	18.7	21.1	16.6	17.8	19.7
	19.3	21.5	21.2	20.0	18.8	20.6	22.4	18.8	21.8	19.5	20.3	20.5
	23.5	23.0	22.7	22.3	24.5	25.5	22.7	20.7	21.9	26.6	24.6	27.1
$\overline{P}$	28.1	27.0	27.0	27.5	26.9	29.7	26.7	26.2	26.5	25.8	29.3	28.5
	29.9	28.4	28.4	29.2	28.7	30.6	28.8	28.2	28.4	28.9	30.5	29.1
	30.0	29.3	29.2	28.8	30.1	30.6	29.0	27.5	29.1	28.3	30.6	30.4
	26.0	19.8	20.1	22.4	25.9	28.4	17.5	20.5	18.6	27.6	26.4	25.8
	15.3	11.2	8.5	8.3	16.5	14.9	8.5	9.2	9.7	20.5	15.6	16.4
	7.4	5.4	5.5	7.4	4.7	6.3	5.6	4.3	4.8	10.4	7.7	6.0
	3.5	4.9	3.7	4.1	4.7	8.5	6.0	2.8	5.1	6.8	3.7	6.8

Table A5. Climate patterns under the 1.5 °C warming scenario.

Site	CZ	GY	GZ	HY	HZ	LF	LZ	MX	SG	XW	YJ	ZS
$\overline{R}$	13.0	11.0	11.6	12.4	12.1	13.4	9.8	12.2	10.4	13.2	13.4	12.4
	11.4	9.4	9.9	10.5	10.9	12.1	8.3	10.3	8.6	13.6	12	11.1
	12.7	11.1	11.2	11.8	12.4	13.9	10.0	11.4	9.9	15.7	13.9	12.7
	14.1	12.4	12.3	13.2	14.7	14.2	10.8	12.8	10.9	18.2	14.1	13.2
	15.6	14.4	14.6	15.2	17.0	17.2	12.8	14.7	13.1	20.2	17.1	16.3
	15.2	15.6	15.5	15.1	16.2	16.8	14.0	14.5	14.3	18.9	16.7	16
	18.3	17.7	17.7	17.8	17.0	19.9	16.6	18.1	16.8	20.0	19.9	17.5
	18.1	17.7	17.9	17.9	17.4	19.7	16.9	17.9	17.0	18.7	19.6	18.4
	16.7	16.1	16.5	16.8	16.6	18.2	15.1	16.2	15.2	17.0	18.1	17.6
	15.6	15.0	15.3	15.6	16.1	17.2	13.7	15.1	14.2	16.0	17.1	16.7
	14.2	14.8	14.9	14.6	14.9	15.4	13.8	13.9	14.2	14.9	15.3	14.8
	12.9	12.2	12.2	12.8	12.4	13.3	10.8	12.7	11.4	12.9	13.2	12.4
$\overline{TM}$	18.9	17.5	18.8	19.0	20.2	19.4	14.0	17.3	15.9	21.7	19.5	18.2
	20.3	19.1	20.4	20.5	21.4	20.8	15.8	18.9	17.7	24.0	21.1	19.5
	22.2	21.2	22.4	22.6	23.3	22.8	18.1	21.3	19.8	27.0	23.4	22
	25.4	24.8	25.9	26.2	27.5	25.7	22.4	24.9	23.8	30.5	26.6	25.4
	28.8	29.2	30.2	29.9	31.7	28.9	27.1	28.4	28.4	33.4	30.1	29.5
	30.6	31.3	32.2	31.3	33	30.7	29.6	30.2	31.0	34.1	31.8	31.1
	32.5	32.7	33.5	32.8	33.3	31.9	31.4	32.3	32.8	34.2	33.3	32.1
	33.0	33.0	33.9	33.4	33.3	32.5	31.6	32.5	33.1	33.6	33.7	32.3
	32.0	31.8	32.8	32.4	32.4	31.9	29.9	31.1	31.5	32.5	32.6	31.4
	29.7	29.2	30.3	30.1	30.3	29.9	26.8	28.6	28.5	30.3	30.1	29
	26.2	25.4	26.7	26.4	27.4	26.7	22.7	25.0	24.4	27.4	26.4	25.3
	21.1	19.8	21.0	21.2	22.3	21.7	16.8	19.6	18.5	22.9	21.5	20.4
$\overline{TN}$	10.9	9.7	10.8	10.3	13.5	12.0	6.1	7.5	7.5	15.3	11.9	11.6
	13.5	12.7	13.8	13.2	15.8	14.4	9.1	10.7	10.7	17.5	14.4	14.1
	15.5	14.6	15.9	15.3	17.8	16.5	11.2	13.2	12.8	19.6	16.5	16.7
	19.2	18.5	19.8	19.5	21.5	20	15.5	17.2	17.2	23	20	20.3
	23.2	22.9	24.1	23.4	25.3	23.7	20.3	21.1	21.9	25.8	23.7	24.1
	25.7	25.5	26.6	26.1	26.8	26.3	23.4	23.9	24.9	27.2	26.4	26.4
	26.2	25.8	26.8	26.3	26.8	26.6	24.0	24.4	25.3	27.1	26.5	26.8
	26.1	25.2	26.4	26.0	26.3	26.4	23.3	24.1	24.6	26.5	26.2	26.3
	25.1	24.4	25.5	25.1	25.6	25.6	22.0	22.8	23.4	26	25.5	25.5
	22.2	21.1	22.5	22.2	23.3	23.1	18.1	19.3	19.6	24.3	22.9	23.1
	17.7	15.8	17.2	17.1	19.6	18.7	12.3	14.2	13.9	21.2	18.6	18.9
	12.4	10.9	12.1	11.7	14.9	13.5	7.2	8.7	8.6	16.7	13.5	13.7
$\overline{P}$	7.6	6.7	5.3	7.3	7.2	7.4	9.1	7.0	6.7	9.3	6.6	6.5
	15.2	17.2	16.6	15.2	16.9	15.0	17.4	15.5	17.3	15.1	14.8	14.9
	13.8	16.5	16.5	16.4	15.8	15.1	19.9	15.4	19.5	16	15	17
	21.8	23.7	23.6	22.9	20.8	22.4	24.7	21.1	23.9	21.8	22.1	22.9
	25.0	25.3	24.8	23.2	26.7	27.7	24.8	21.3	24.4	27.0	27.2	28
	27.7	26.9	26.9	27.9	26.7	29.3	27.1	27.9	26.9	27.0	28.9	27.9
	29.0	28.7	28.6	28.9	30.2	30.3	28.6	26.9	28.6	29.2	30.1	29.5
	30.2	28.8	28.8	29.2	30.0	30.6	27.7	27.8	28.0	28.1	30.6	30.2
	24.8	21.8	22.0	22.1	26.5	28.6	19.7	20.8	20.7	27.6	26.8	26.2
	16.8	11.2	9.1	7.8	15.1	15.0	9.5	12.9	9.5	18.3	15	15.7
	6.3	4.2	7.0	9.2	6.9	6.8	5.6	3.4	4.4	13.0	7.5	8.3
	4.1	5.1	5.1	5.9	5.7	7.5	5.5	3.4	5.2	8.4	5.7	6.1

Table A6. Climate patterns under the 2.0 °C warming scenario.

Site	CZ	GY	GZ	HY	HZ	LF	LZ	MX	SG	XW	YJ	ZS
	12.8	10.5	11.1	12.2	11.7	13.0	9.2	12.0	9.8	12.6	13.0	11.9
	11.1	9.4	9.8	10.4	10.8	11.6	8.3	10.0	8.6	12.4	11.5	10.2
	12.5	11.1	11.2	11.8	13.1	13.5	9.9	11.2	9.8	15.5	13.5	11.8
	14.6	13.8	13.8	14	15.7	15.4	12.2	13.3	12.4	17.9	15.3	13.9
	15.5	15.4	15.6	15.3	17.4	16.9	13.8	14.6	14.1	20.8	16.8	16.4
$\overline{R}$	15.9	15.7	15.7	15.6	16.9	17.8	14.1	15.2	14.3	20.4	17.7	17.0
	20.2	19.7	19.8	19.5	19.2	21.9	18.6	19.9	18.9	21.7	21.9	20.3
	16.6	16.7	16.9	16.6	17.0	18.1	15.9	16.5	15.9	18.8	18.0	17.2
	16.1	15.8	16.2	16.4	16.5	18.1	14.8	15.7	14.9	17.6	18.0	16.9
	15.3	15.3	15.7	15.6	16.1	17.0	14.1	14.9	14.6	15.8	16.8	16.0
	14.5	14.8	15.0	15.0	14.7	15.3	13.8	14.2	14.2	13.9	15.2	14.4
	12.7	11.9	11.9	12.4	11.8	13.0	10.5	12.4	11.2	12.7	12.9	11.7
	19.2	17.6	19.0	19.1	20.5	19.7	14.1	17.5	16.0	21.8	19.8	18.4
	20.2	18.7	20.0	20.2	21.4	20.7	15.4	18.8	17.3	23.8	21.0	19.3
	22.5	21.5	22.7	22.9	24.1	23.1	18.5	21.6	20.2	27.2	23.7	22.3
	26.0	25.5	26.6	26.7	28.1	26.2	23.1	25.5	24.5	30.6	27.1	26.0
	29.5	29.9	31.0	30.6	32.3	29.6	27.9	29.1	29.2	34.3	30.7	30.1
$\overline{TM}$	31.4	31.9	32.9	32.1	33.9	31.4	30.3	31.0	31.7	35.3	32.5	31.9
	33.5	34.0	34.8	33.9	34.7	32.9	32.7	33.3	34.1	35.2	34.4	33.2
	33.3	33.4	34.3	33.7	34.2	32.9	32.0	32.8	33.4	34.4	34.0	32.7
	32.5	32.0	33.0	32.8	33.1	32.5	30.1	31.5	31.7	33.3	33.1	32.1
	30.1	29.5	30.7	30.5	31.0	30.4	27.1	29.0	28.9	30.8	30.5	29.4
	26.5	25.7	26.9	26.7	27.7	27.0	22.9	25.2	24.7	27.5	26.7	25.6
	21.4	20.2	21.5	21.4	22.9	22.0	17.2	20.0	18.9	23.4	21.9	20.9
	11.1	9.8	10.9	10.5	13.7	12.2	6.1	7.7	7.6	15.5	12.2	11.9
	13.7	12.4	13.5	13.2	15.9	14.6	8.8	10.9	10.4	17.6	14.6	14.2
	16.1	15.3	16.5	16.0	18.6	17.1	11.9	13.9	13.5	20.1	17.1	17.1
	19.5	18.9	20.1	19.7	22.2	20.2	15.9	17.6	17.6	23.4	20.2	20.7
	23.7	23.0	24.2	23.9	26.0	24.1	20.4	21.7	22.0	26.2	24.2	24.5
$\overline{TN}$	26.1	25.8	26.9	26.4	27.7	26.6	23.7	24.3	25.2	27.7	26.6	26.9
	26.5	25.8	26.9	26.5	27.7	26.8	24.0	24.6	25.3	27.3	26.6	27.2
	26.8	25.9	27.0	26.7	27.3	26.9	23.9	24.8	25.3	27.1	26.8	26.9
	25.5	24.7	25.9	25.5	26.1	26.0	22.3	23.2	23.7	26.3	25.8	25.8
	22.4	21.1	22.5	22.2	23.7	23.2	18.1	19.4	19.6	24.7	23.0	23.3
	17.6	16.0	17.4	17.1	19.9	18.7	12.5	14.0	14.1	21.2	18.5	19.0
	12.7	11.3	12.5	11.9	15.4	13.8	7.6	9.0	9.0	17.1	13.8	14.0
	6.4	6.6	5.6	5.4	5.9	5.2	8.4	6.1	6.8	7.2	4.3	5.2
	13.1	16.0	15.8	14.1	15.3	14.4	16.6	13.7	16.4	13.5	14.3	15.0
	14.7	18.1	18.1	17.3	16.0	16.1	20.2	16.8	19.9	16.2	15.3	16.8
	19.1	21.8	21.4	20.4	19.6	18.0	22.9	18.1	21.9	19.9	17.7	19.1
	25.5	24.5	24.3	23.3	25.7	27.5	24.3	22.1	24.0	26.9	26.8	28.1
$\overline{P}$	27.6	26.7	26.7	27.7	26.6	29.2	26.8	26.8	26.6	26.6	28.5	28.7
	27.9	27.1	27.0	26.6	27.6	29.8	26.9	24.0	27	27.5	29.3	28.2
	29.7	28.0	28.0	29.0	29.6	30.1	27.6	27.3	27.8	29.9	30.0	30.3
	23.9	18.0	18	20.2	24.4	25.8	15.7	19.6	16.7	27.8	23.9	24.7
	14.6	9.9	9.7	8.6	13.4	13.6	9.8	8.1	8.1	16.9	14.7	15.0
	6.4	4.1	5.6	6.8	5.8	7.2	5.5	3.7	4.4	10.4	7.4	7.3
	5.3	5.8	4.9	6.7	7.3	8.5	5.9	5.0	5.8	8.3	6.3	6.8

References

1. Klutse, N.A.B.; Ajayi, V.O.; Gbobaniyi, E.O.; Egbebiyi, T.S.; Kouadio, K.; Nkrumah, F.; Quagraine, K.A.; Olusegun, C.; Diasso, U.; Abiodun, B.J. Potential impact of 1.5 °C and 2 °C global warming on consecutive dry and wet days over west africa. *Environ. Res. Lett.* **2018**, *13*, 055013. [CrossRef]
2. Rogelj, J.; Popp, A.; Calvin, K.V.; Luderer, G.; Emmerling, J.; Gernaat, D.; Fujimori, S.; Strefler, J.; Hasegawa, T.; Marangoni, G. Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat. Clim. Chang.* **2018**, *8*, 325–332. [CrossRef]
3. Harvey, L.D. *Global Warming*; Routledge: London, UK, 2018.
4. Edenhofer, O.; Seyboth, K. Intergovernmental panel on climate change (IPCC). *Encycl. Energy Nat. Resour. Environ. Econ.* **2013**, *26*, 48–56.
5. Vuuren, D.P.V.; Stehfest, E.; Elzen, M.G.J.D.; Kram, T.; Vliet, J.V.; Deetman, S.; Isaac, M.; Goldewijk, K.K.; Hof, A.; Beltran, A.M. Rcp2.6: Exploring the possibility to keep global mean temperature increase below 2 °C. *Clim. Chang.* **2011**, *109*, 95–116. [CrossRef]
6. Zhao, C.; Liu, B.; Piao, S.; Wang, X.; Lobell, D.B.; Huang, Y.; Huang, M.; Yao, Y.; Bassu, S.; Ciais, P. Temperature increase reduces global yields of major crops in four independent estimates. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 9326–9331. [CrossRef] [PubMed]
7. Viceto, C.; Cardoso Pereira, S.; Rocha, A. Climate change projections of extreme temperatures for the iberian peninsula. *Atmosphere* **2019**, *10*, 229. [CrossRef]
8. Blau, J. *The Paris Agreement*; Springer: Berlin, Germany, 2017.
9. Falkner, R. The paris agreement and the new logic of international climate politics. *Int. Aff.* **2016**, *92*, 1107–1125. [CrossRef]
10. Rogelj, J.; Den, E.M.; Höhne, N.; Fransen, T.; Fekete, H.; Winkler, H.; Schaeffer, R.; Sha, F.; Riahi, K.; Meinshausen, M. Paris agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **2016**, *534*, 631–639. [CrossRef]
11. Roy, J.; Tschakert, P.; Waisman, H.; Halim, S.A.; Antwi-Agyei, P.; Dasgupta, P.; Hayward, B.; Kanninen, M.; Liverman, D.; Okereke, C. Sustainable development, poverty eradication and reducing inequalities. In *Global Warming of 1.5 °C*; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2018.
12. Hatfield, J.L.; Boote, K.J.; Kimball, B.A.; Ziska, L.H.; Izaurralde, R.C.; Ort, D.; Thomson, A.M.; Wolfe, D. Climate impacts on agriculture: Implications for crop production. *Agron. J.* **2011**, *103*, 351–370. [CrossRef]
13. Jabloun, M.; Schelde, K.; Tao, F.; Olesen, J.E. Effect of temperature and precipitation on nitrate leaching from organic cereal cropping systems in denmark. *Eur. J. Agron.* **2015**, *62*, 55–64. [CrossRef]
14. Daničić, M.; Zekić, V.; Mirosavljević, M.; Lalić, B.; Putnik-Delić, M.; Maksimović, I.; Dalla Marta, A. The response of spring barley (*Hordeum vulgare* L.) to climate change in northern serbia. *Atmosphere* **2019**, *10*, 14. [CrossRef]
15. Nie, H.; Qin, T.; Yang, H.; Chen, J.; He, S.; Lv, Z.; Shen, Z. Trend analysis of temperature and precipitation extremes during winter wheat growth period in the major winter wheat planting area of China. *Atmosphere* **2019**, *10*, 240. [CrossRef]
16. Mitchell, D.; Achutarao, K.; Allen, M.; Bethke, I.; Beyerle, U.; Ciavarella, A.; Forster, P.M.; Fuglestvedt, J.; Gillett, N.; Haustein, K. Half a degree additional warming, prognosis and projected impacts (HAPPI): Background and experimental design. *Geosci. Model Dev.* **2017**, *10*, 571–583. [CrossRef]
17. Drobinski, P.; Silva, N.D.; Panthou, G.; Bastin, S.; Muller, C.; Ahrens, B.; Borga, M.; Conte, D.; Fosser, G.; Giorgi, F. Scaling precipitation extremes with temperature in the mediterranean: Past climate assessment and projection in anthropogenic scenarios. *Clim. Dyn.* **2018**, *51*, 1237–1257. [CrossRef]
18. Arora, V.; Scinocca, J.; Boer, G.; Christian, J.; Denman, K.; Flato, G.; Kharin, V.; Lee, W.; Merryfield, W. Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases. *Geophys. Res. Lett.* **2011**, *38*. [CrossRef]
19. Van Vuuren, D.P.; Edmonds, J.; Kainuma, M.; Riahi, K.; Thomson, A.; Hibbard, K.; Hurtt, G.C.; Kram, T.; Krey, V.; Lamarque, J.-F. The representative concentration pathways: An overview. *Clim. Chang.* **2011**, *109*, 5–31. [CrossRef]

20. Jones, C.; Robertson, E.; Arora, V.; Friedlingstein, P.; Shevliakova, E.; Bopp, L.; Brovkin, V.; Hajima, T.; Kato, E.; Kawamiya, M. Twenty-first-century compatible CO_2 emissions and airborne fraction simulated by cmip5 earth system models under four representative concentration pathways. *J. Clim.* **2013**, *26*, 4398–4413. [CrossRef]
21. Amouzou, K.A.; Naab, J.B.; Lamers, J.P.A.; Becker, M. Ceres-maize and ceres-sorghum for modeling growth, nitrogen and phosphorus uptake, and soil moisture dynamics in the dry savanna of West Africa. *Field Crops Res.* **2017**, *217*, 134–149. [CrossRef]
22. Jahan, M.A.H.S.; Sen, R.; Ishtiaque, S.; Choudhury, A.K.; Akhter, S.; Ahmed, F.; Biswas, J.C.; Manirruzaman, M.; Miah, M.M.; Rahman, M.M. Optimizing sowing window for wheat cultivation in bangladesh using ceres-wheat crop simulation model. *Agric. Ecosyst. Environ.* **2018**, *258*, 23–29. [CrossRef]
23. Yin, Y.; Tang, Q.; Liu, X. A multi-model analysis of change in potential yield of major crops in China under climate change. *Earth Syst. Dyn.* **2015**, *6*, 45–59. [CrossRef]
24. Xu, C.-C.; Wu, W.-X.; Ge, Q.-S.; Zhou, Y.; Lin, Y.-M.; Li, Y.-M. Simulating climate change impacts and potential adaptations on rice yields in the sichuan basin, china. *Mitig. Adapt. Strateg. Glob. Chang.* **2015**, *22*, 565–594. [CrossRef]
25. Li, Y.; Wu, W.; Ge, Q.; Zhou, Y.; Xu, C. Simulating climate change impacts and adaptive measures for rice cultivation in Hunan province, China. *J. Appl. Meteorol. Climatol.* **2016**, *55*, 1359–1376. [CrossRef]
26. Chen, Y.; Zhang, Z.; Tao, F. Impacts of climate change and climate extremes on major crops productivity in China at a global warming of 1.5 and 2.0 °C. *Earth Syst. Dyn.* **2018**, *9*, 543–562. [CrossRef]
27. Jacob, D.; Kotova, L.; Teichmann, C.; Sobolowski, S.P.; Vautard, R.; Donnelly, C.; Koutroulis, A.G.; Grillakis, M.G.; Tsanis, I.K.; Damm, A.; et al. Climate impacts in europe under +1.5 °C global warming. *Earth's Future* **2018**, *6*, 264–285. [CrossRef]
28. Tao, F.; Yokozawa, M.; Liu, J.; Zhang, Z. Climate–crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Clim. Res.* **2008**, *38*, 83–94. [CrossRef]
29. Tao, F.; Yokozawa, M.; Xu, Y.; Hayashi, Y.; Zhang, Z. Climate changes and trends in phenology and yields of field crops in China, 1981–2000. *Agric. For. Meteorol.* **2006**, *138*, 82–92. [CrossRef]
30. Yao, F.; Xu, Y.; Feng, Q.; Lin, E.; Yan, X. Simulation and validation of ceres—Rice model in main rice ecological zones in China. *Acta Agron. Sin.* **2005**, *31*, 545–550.
31. Guo, Y.; Wu, W.; Du, M.; Bryant, C.R.; Li, Y.; Wang, Y.; Huang, H. Assessing potential climate change impacts and adaptive measures on rice yields: The case of zhejiang province in China. *Sustainability* **2019**, *11*, 2372. [CrossRef]
32. Shi, Q.-H.; Liu, J.-G.; Wang, Z.-H.; Tao, T.-T.; Chen, F.; Chu, Q.-Q. Change of rice yield gaps and influential climatic factors in southern China. *Acta Agron. Sin.* **2013**, *38*, 896–903. [CrossRef]
33. Xu, X.Q.; Li, S.M. China's open door policy and urbanization in the pearl river delta region. *Int. J. Urban Reg. Res.* **1990**, *14*, 49–69.
34. He, G.; Wang, Z.; Wang, M.; Zou, X.; Liu, J.; Wang, S.; Hou, Y. Genetic variations and forensic characteristics of han Chinese population residing in the pearl river delta revealed by 23 autosomal strs. *Mol. Biol. Rep.* **2018**, *45*, 1125–1133. [CrossRef] [PubMed]
35. National Bureau of Statistics. Available online: http://www.stats.gov.cn/ (accessed on 11 July 2019).
36. Zhou, G.; Wei, X.; Yan, L.; Zhang, M.; Li, Y.; Qiao, Y.; Liu, H.; Wang, C. Forest recovery and river discharge at the regional scale of Guangdong province, China. *Water Resour. Res.* **2010**, *46*, 5109–5115. [CrossRef]
37. Jones, J.W.; Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Batchelor, W.D.; Hunt, L.; Wilkens, P.W.; Singh, U.; Gijsman, A.J.; Ritchie, J.T. The dssat cropping system model. *Eur. J. Agron.* **2003**, *18*, 235–265. [CrossRef]
38. Jones, J.; Tsuji, G.; Hoogenboom, G.; Hunt, L.; Thornton, P.; Wilkens, P.; Imamura, D.; Bowen, W.; Singh, U. Decision support system for agrotechnology transfer: Dssat v3. In *Understanding Options for Agricultural Production*; Springer: Berlin, Germany, 1998; pp. 157–177.
39. Gijsman, A.J.; Hoogenboom, G.; Parton, W.J.; Kerridge, P.C. Modifying dssat crop models for low-input agricultural systems using a soil organic matter–residue module from century. *Agron. J.* **2002**, *94*, 462–474. [CrossRef]
40. Ahmed, M.; Akram, M.N.; Asim, M.; Aslam, M.; Hassan, F.-U.; Higgins, S.; Stöckle, C.O.; Hoogenboom, G. Calibration and validation of apsim-wheat and ceres-wheat for spring wheat under rainfed conditions: Models evaluation and application. *Comput. Electron. Agric.* **2016**, *123*, 384–401. [CrossRef]

41. Amiri, E.; Rezaei, M.; Rezaei, E.E.; Bannayan, M. Evaluation of ceres-rice, aquacrop and oryza 2000 models in simulation of rice yield response to different irrigation and nitrogen management strategies. *J. Plant Nutr.* **2014**, *37*, 1749–1769. [CrossRef]
42. Jones, J.W.; Antle, J.M.; Basso, B.; Boote, K.J.; Conant, R.T.; Foster, I.; Godfray, H.C.J.; Herrero, M.; Howitt, R.E.; Janssen, S.; et al. Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science. *Agric. Syst.* **2017**, *155*, 269–288. [CrossRef] [PubMed]
43. Jones, J.W.; Antle, J.M.; Basso, B.; Boote, K.J.; Conant, R.T.; Foster, I.; Godfray, H.C.J.; Herrero, M.; Howitt, R.E.; Janssen, S.; et al. Brief history of agricultural systems modeling. *Agric. Syst.* **2017**, *155*, 240–254. [CrossRef] [PubMed]
44. Esteves, M.; Román-Paoli, E.; Beaver, J.S.; Muñoz, M.A.; Armstrong, A. Genetic coefficient determination for three maize cultivars and one hybrid. *J. Agric. Univ. Puerto Rico* **2012**, *96*, 57–75.
45. Guo, Y.; Wu, W.; Bryant, C.R. Quantifying spatio-temporal patterns of rice yield gaps in double-cropping systems: A case study in pearl river delta, China. *Sustainability* **2019**, *11*, 1394. [CrossRef]
46. Van Bussel, L.G.J.; Grassini, P.; Van Wart, J.; Wolf, J.; Claessens, L.; Yang, H.; Boogaard, H.; de Groot, H.; Saito, K.; Cassman, K.G.; et al. From field to atlas: Upscaling of location-specific yield gap estimates. *Field Crops Res.* **2015**, *177*, 98–108. [CrossRef]
47. Lychuk, T.E.; Hill, R.L.; Izaurralde, R.C.; Momen, B.; Thomson, A.M. Evaluation of climate change impacts and effectiveness of adaptation options on crop yield in the southeastern United States. *Field Crops Res.* **2017**, *214*, 228–238. [CrossRef]
48. Onoyama, H.; Ryu, C.; Suguri, M.; Iida, M. Nitrogen prediction model of rice plant at panicle initiation stage using ground-based hyperspectral imaging: Growing degree-days integrated model. *Precis. Agric.* **2015**, *16*, 558–570. [CrossRef]
49. Thaler, S.; Brocca, L.; Ciabatta, L.; Eitzinger, J.; Hahn, S.; Wagner, W. Effects of different spatial precipitation input data on crop model outputs under a central European climate. *Atmosphere* **2018**, *9*, 290. [CrossRef]
50. Yan, D.C.; Yan, Z.; Wang, S.H.; Cao, W.X. A quantitative knowledge-based model for designing suitable growth dynamics in rice. *Plant Prod. Sci.* **2006**, *9*, 93–105. [CrossRef]
51. Lewis, S.E.; Rice, A.; Hurst, G.D.D.; Baylis, M. First detection of endosymbiotic bacteria in biting midges culicoides pulicaris and culicoides punctatus, important palaearctic vectors of bluetongue virus. *Med. Vet. Entomol.* **2015**, *28*, 453–456. [CrossRef] [PubMed]
52. Ying, M.; Zhang, W.; Yu, H.; Lu, X.; Feng, J.; Fan, Y.; Zhu, Y.; Chen, D. An overview of the China meteorological administration tropical cyclone database. *J. Atmos. Ocean. Technol.* **2014**, *31*, 287–301. [CrossRef]
53. National Meteorological Information Center. Available online: http://data.cma.cn/ (accessed on 11 July 2019).
54. Zhang, S.; Tao, F. Modeling the response of rice phenology to climate change and variability in different climatic zones: Comparisons of five models. *Eur. J. Agron.* **2013**, *45*, 165–176. [CrossRef]
55. Shi, X.Z.; Yu, D.S.; Pan, X.Z.; Sun, W.X.; Gong, Z.G.; Warner, E.D.; Petersen, G.W. A Framework for the 1:1,000,000 Soil Database of China. In Proceedings of the 17th World Congress of Soil Science, Bangkok, Thailand, 14–21 August 2002.
56. Soil Science Database. Available online: http://vdb3.soil.csdb.cn/ (accessed on 11 July 2019).
57. Zhou, Q.; Wang, M.; Zhong, X.; Liu, P.; Xie, X.; Wangxiao, J.; Sun, Y. Dissemination of resistance genes in duck/fish polyculture ponds in Guangdong province: Correlations between cu and zn and antibiotic resistance genes. *Environ. Sci. Pollut. Res.* **2019**, *26*, 8182–8193. [CrossRef]
58. Tao, F.; Zhang, S.; Zhang, Z.; Rötter, R.P. Maize growing duration was prolonged across China in the past three decades under the combined effects of temperature, agronomic management, and cultivar shift. *Glob. Chang. Biol.* **2014**, *20*, 3686–3699. [CrossRef]
59. *China Meteorological Administration*; China Intercontinental Communication Co., Ltd: Beijing, China, 2014.
60. Hoang, L.; Ngoc, T.A.; Maskey, S. A robust parameter approach for estimating ceres-rice model parameters for the vietnam mekong delta. *Field Crops Res.* **2016**, *196*, 98–111. [CrossRef]
61. Cao, X.X.; An, K.Z.; Cai, W.; Su, R.R.; Yao, F.M. Validation and adaptability evaluation of ceres-rice model in the Jianghan plain. *Chin. J. Agrometeorol.* **2013**, *34*, 447–454.
62. Cheyglinted, S.; Ranamukhaarachchi, S.L.; Singh, G. Assessment of the ceres-rice model for rice production in the central plain of Thailand. *J. Agric. Sci.* **2001**, *137*, 289–298. [CrossRef]
63. Jones, J.W.; He, J.; Boote, K.J.; Wilkens, P.; Porter, C.H.; Hu, Z. Estimating dssat cropping system cultivar-specific parameters using bayesian techniques. *Methods Introd. Syst. Models Into. Agric. Res.* **2011**. [CrossRef]

64. Ahmad, A.; Ali, A.; Khaliq, T.; Wajid, S.A.; Iqbal, Z.; Ibrahim, M.; Javeed, H.M.R.; Hoogenboom, G. Oilcrop-sun model relevance for evaluation of nitrogen management of sunflower hybrids in Sargodha, Punjab. *Am. J. Plant Sci.* **2013**, *4*, 1731–1735. [CrossRef]
65. RCP Datatbase. Version 2.0.5. Available online: http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=compare (accessed on 11 July 2019).
66. Guo, Y.; Senthilnath, J.; Wu, W.; Zhang, X.; Zeng, Z.; Huang, H. Radiometric calibration for multispectral camera of different imaging conditions mounted on a uav platform. *Sustainability* **2019**, *11*, 978. [CrossRef]
67. Grassini, P.; van Bussel, L.G.J.; Van Wart, J.; Wolf, J.; Claessens, L.; Yang, H.; Boogaard, H.; de Groot, H.; van Ittersum, M.K.; Cassman, K.G. How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. *Field Crops Res.* **2015**, *177*, 49–63. [CrossRef]
68. Zhu, S.; Zhang, H.; Gang, W.; Qian, G. Interpretation of international cooperation on mitigation from IPCC fifth assessment report. *Prog. Inquisitiones Mutat. Clim.* **2014**, *59*, 901–913.
69. Amiri, E.; Rezaei, M.; Bannayan, M.; Soufizadeh, S. Calibration and evaluation of ceres rice model under different nitrogen- and water-management options in semi-mediterranean climate condition. *Commun. Soil Sci. Plant Anal.* **2013**, *44*, 1814–1830. [CrossRef]
70. Feldmeyer, D.; Wilden, D.; Kind, C.; Kaiser, T.; Goldschmidt, R.; Diller, C.; Birkmann, J. Indicators for monitoring urban climate change resilience and adaptation. *Sustainability* **2019**, *11*, 2931. [CrossRef]
71. Beza, E.; Silva, J.V.; Kooistra, L.; Reidsma, P. Review of yield gap explaining factors and opportunities for alternative data collection approaches. *Eur. J. Agron.* **2017**, *82*, 206–222. [CrossRef]
72. Bryant, C.R.; Sarr, M.A.; Delusca, K. *Agricultural Adaptation to Climate Change*; Springer: Berlin, Germany, 2016.
73. Jiang, M.; Shi, C.L.; Liu, Y.; Jin, Z.Q. Response of rice production to climate change based on self-adaptation in fujian province. *J. Agric. Sci.* **2017**, *155*, 751–765. [CrossRef]
74. Biber, D. Pearson Correlation Coefficients for All Linguistic Features. In *Variation Across Speech and Writing*; Cambridge University Press: Cambridge, UK, 1988.
75. Ahlgren, P.; Bo, J.; Rousseau, R. Requirements for a cocitation similarity measure, with special reference to pearson's correlation coefficient. *J. Assoc. Inf. Sci. Technol.* **2014**, *54*, 550–560. [CrossRef]
76. Byjesh, K.; Kumar, S.N.; Aggarwal, P.K. Simulating impacts, potential adaptation and vulnerability of maize to climate change in India. *Mitig. Adapt. Strateg. Glob. Chang.* **2010**, *15*, 413–431. [CrossRef]
77. Deryng, D.; Sacks, W.J.; Barford, C.C.; Ramankutty, N. Simulating the effects of climate and agricultural management practices on global crop yield. *Glob. Biogeochem. Cycles* **2011**, *25*. [CrossRef]
78. Srivastava, A.K.; Gaiser, T.; Ewert, F. Climate change impact and potential adaptation strategies under alternate climate scenarios for yam production in the sub-humid savannah zone of West Africa. *Mitig. Adapt. Strateg. Glob. Chang.* **2016**, *21*, 955–968. [CrossRef]
79. Saseendran, S.A.; Singh, K.K.; Rathore, L.S.; Singh, S.V.; Sinha, S.K. Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Clim. Chang.* **2000**, *44*, 495–514. [CrossRef]
80. Lansigan, F.P.; Santos, W.L.D.L.; Coladilla, J.O. Agronomic impacts of climate variability on rice production in the philippines. *Agric. Ecosyst. Environ.* **2000**, *82*, 129–137. [CrossRef]
81. Shi, W.; Tao, F. Vulnerability of african maize yield to climate change and variability during 1961–2010. *Food Secur.* **2014**, *6*, 471–481. [CrossRef]
82. Yang, D.; Xiong, W.; Xu, Y.; Feng, L.; Liu, H. Analysis of reason for recent slowing maize yield increase under climate change in China. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 231–238.
83. Zhai, S.; Song, G.; Qin, Y.; Ye, X.; Lee, J. Modeling the impacts of climate change and technical progress on the wheat yield in inland China: An autoregressive distributed lag approach. *PLoS ONE* **2017**, *12*, e0184474. [CrossRef]
84. Zhang, X.; Xu, M.; Nan, S.; Wei, X.; Huang, S.; Wu, L. Modelling and predicting crop yield, soil carbon and nitrogen stocks under climate change scenarios with fertiliser management in the north China plain. *Geoderma* **2016**, *265*, 176–186. [CrossRef]