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Determination of Nitrogen Application Ratio and Sowing Time for Improving the Future Yield of Double-Harvest Rice in Nanchang Based on the DSSAT-CERES-Rice Model

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Abstract: Climate change is a very serious threat to the agricultural sector and potentially brings new problems to the sustainability of agricultural production systems. This paper aims to know how to improve crop yield by changing the nitrogen application ratio and sowing time under future climate change conditions based on the CERES-Rice model. The CERES-Rice model was calibrated and validated with a three-year field experiment (2018–2020), which was coupled with four N rates (50, 100, 150, and 200 kg/ha) and three different N ratios (B:T:S = 3:1:0; B:T:S = 5:3:2; B:T:S = 6:3:1). The results showed that the CERES-Rice model had better simulation effect on the phenophase (n-RMSE < 15%, d > 0.9 and R^2 = 0.978) and yield (n-RMSE < 10%, d > 0.9 and R^2 = 0.910) of double-harvest rice. The calibrated model was used to evaluate the growth period and yield of double-harvest rice under the RCP4.5 climate scenario and the results revealed that future yields of double-harvest rice in Nanchang are lower than those in experimental years, especially for early rice. Adjusting the nitrogen application ratio and sowing time can improve the yield of double-harvest rice to a certain extent, and the nitrogen application ratio of 5:3:2 has the best effect. In 2021–2035, the best yield of double-harvest rice can be obtained when the sowing date of early rice is about 15 days earlier and the sowing date of late rice is about 10 days earlier than the experiment year. From 2035 to 2050, the sowing date of early rice and late rice will be advanced by about 10 days, and the total yield of double-harvest rice will be higher. In 2050–2070, the total yield of double-harvest rice may reach the best when the sowing date is delayed by 10–15 days. Therefore, reasonably changing the sowing date of double-harvest rice and the nitrogen application regime of early rice can be used as a possible adaptive strategy to cope with the yield reduction in double-harvest rice in future climate scenarios.

Keywords: crop model; optimal sowing date; double-harvest rice; grain yield; Nanchang area

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1. Introduction

Rice is one of the main food crops, and more than half of the people in China mainly eat rice [1]. The rice planting areas in China are mainly concentrated in the Yangtze River Basin and the south of China. Among them, double-harvest rice has a wide application area and a high annual yield, which plays an important role in food security in China [2]. Jiangxi Province is the second largest double-harvest rice production area in China, and Po-yang Lake is the main watershed in Jiangxi Province. Double-harvest rice has a longer planting cycle, so it is more affected by the climate than single-harvest rice [3]. Climate change has an important impact on all social fields, among which agriculture is an industry that is greatly affected by climate change and has a weak coping ability [4].

The impact of climate change on crop yield is one of the hot issues in agricultural science and crop safety research in recent years [5,6]. With global climate change and the change of natural climate factors (temperature, precipitation, solar radiation, etc.), the growth and development process of crops and suitable planting areas also change [7,8]. With the continuous emissions of greenhouse gases in the 21st century, surface temperatures will continue to rise, and future global temperatures will show significant warming changes [9,10]. Under high-temperature stress, photosynthetic products in rice and stored substances in stems and leaves could not be effectively transferred to the spikes of crops, resulting in an increase in the proportion of stems and leaves at maturity and a decrease in crop yield [11]. Although there was an increasing trend in rainfall rate and daily rainfall amount in China, the frequency of extreme drought was further increased due to the extension of continuous non-rainfall days in the South [12,13]. The rainfall in Po-yang Lake Basin is mainly concentrated from April to June, while the growth period of double-harvest rice spans from April to October [14]. In the season with less rainfall, double-harvest rice is vulnerable to drought disasters. Therefore, the study on the future climate change trend in Nanchang has an important reference value for the production of double-harvest rice in the region.

Previous researchers used crop models to simulate and predict crop yields in future climate scenarios, climate prediction was mostly based on the RCP4.5 and RCP8.5 emission models proposed [15,16]. Taking the RCP4.5 emission model as the most likely climate model in the future are reliable methods for studying future climate change [17,18]. Zhan et al. [19] made a statistical analysis of climate change in Jiangxi Province based on the data of 15 meteorological stations and GCM data in Jiangxi Province. From 2020 to 2079, the precipitation in Jiangxi Province decreased compared with the base year, and the precipitation and temperature showed an increasing trend. In the study of future climate change in Po-yang Lake by Huang [20] and Islam [21], the temperature of Poyang Lake Basin will show a significant increase trend in the next 50 to 90 years, and the precipitation will increase or change little. Using the existing data to verify the model, it is a hot spot of agricultural model research to simulate and predict the change of crop yield in future climate scenarios based on future climate prediction. Chisanga et al. [22] predicted the future climate in Nanjing from 2016 to 2100, and used the ORYZA2000 model to simulate the rice yield. The influence and response of meteorological factors such as radiation on the future rice yield change were studied. Kontgis et al. [23] calibrated and validated the CERES-Rice model based on experimental data, and maize growth in central Ningxia was simulated and predicted under two future climate scenarios (A2, B2).

In this study, based on the experimental meteorological data of double-harvest rice in Nanchang from 2018 to 2020, the DSSAT-CERES-Rice model was established to simulate and validate the genetic parameters of early and late rice. Based on the GCM down-scaling data of RCP4.5 in the next 50 years (2021–2070), the validated DSSAT-CERES-Rice model was used to simulate and predict the impact of future climate change on the yield of double-cropping rice and the effects of changing double-cropping rice sowing date and fertilizer application ratio on the production of double-cropping rice. The possible adaptation strategies of double-cropping rice production under future climate models were proposed.

2. Materials and Methods

2.1. Study Region

The three-year field experiment was conducted from 2018 to 2020 in Zhongshang Village, Nanchang City, Jiangxi Province, China. The study area is mainly the Po-yang Lake Plain, and the northwest side is the hilly area, which is located at 116°2′46″ east longitude and 28°41′24″ north latitude, with an altitude of 24 m (Figure 1). This area is a tropical monsoon humid climate, with an annual average temperature of 19°C, annual average rainfall of 1500–1600 mm (mostly concentrated from April to June), and a frost-free period of 251–272 days. The paddy red soil (0–20cm) had the following characteristics: pH 5.83 (H_2O), organic matter 15.82 g kg^{-1}, total N 1.32 g kg^{-1}, alkaline hydrolysis N 237.5 mg

kg^{-1}, fast-acting K 276.3 mg kg^{-1}, and available P 16.42 mg kg^{-1}. Rainfall and temperature at the test site are shown in Figure 2.

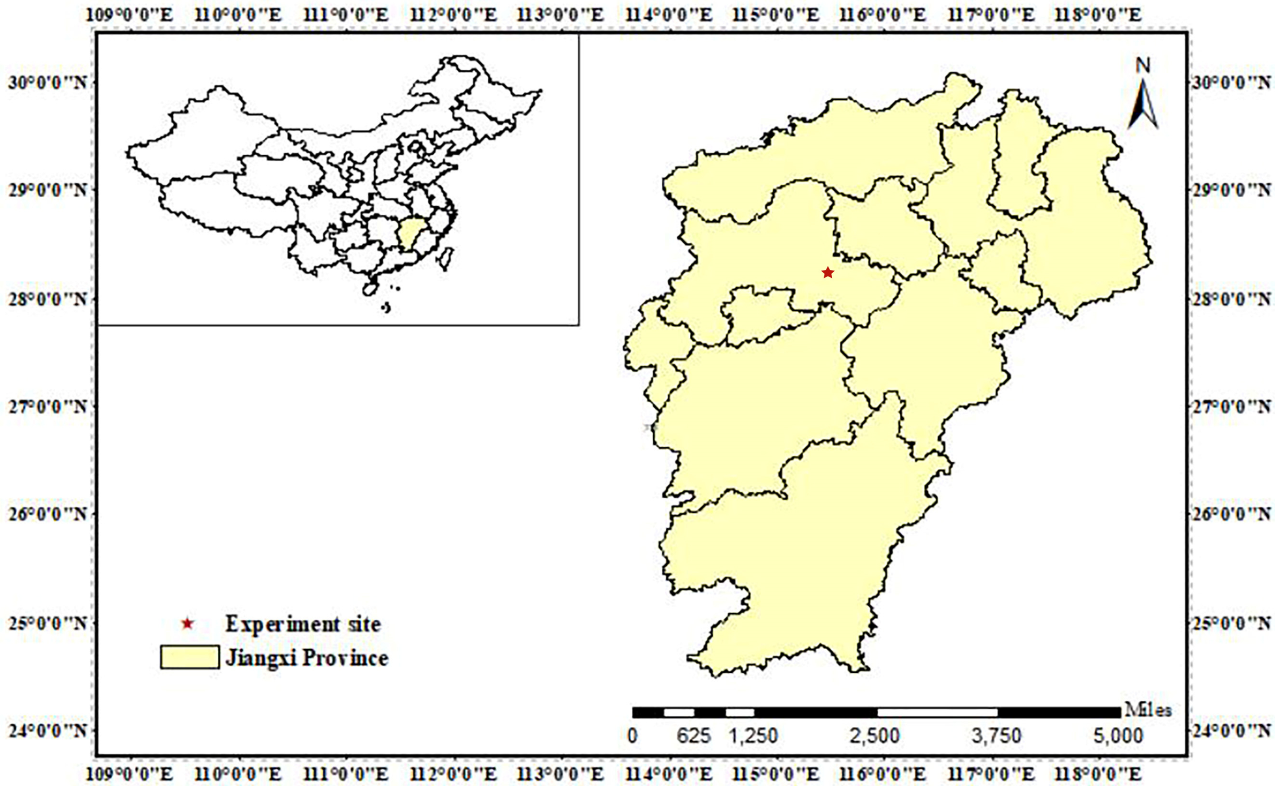

Figure 1. Location map of research site.

2.2. Field Experiment

Early rice variety "Xiang early-indica45" and late rice "Ganwan37" were tested, "Xiang early-indica45" is mainly planted in Hunan, Hubei, Jiangxi, Guangxi, Fujian provinces, the whole growth period is about 106 days, and the plant height is 80–85 cm; "Ganwan37" is a conventional single-season rice variety bred by natural hybridization, the whole growth period is about 126 days, the plant type is moderate, and the tillering ability is strong. The agronomic measures, such as planting mode sowing, planting density, irrigation, and pesticide spraying, were consistent with the local traditional management mode. The experimental set up a total of 13 treatments, each treatment set two replicates, a total of 26 plots, and the area of each plot area is 24 m^2 (2 m $\times$ 12 m). In order to reduce the influence of lateral permeability on the test, each plot was treated with impervious material around, and drainage ditches were set between plots. Early rice-sowing time is 5 April, late rice-sowing time is 23 July, and the traditional sowing method is adopted. We set four different nitrogen levels (F1: 50 kg ha^{-1}; F2: 100 kg ha^{-1}; F3: 150 kg ha^{-1}; F4: 200 kg ha^{-1}) and three different nitrogen ratios (D_1: Basal fertilizer: Tiller fertilizer: Spike fertilize = 3:1:0; D_2: Basal fertilizer: Tiller fertilizer: Spike fertilize = 5:3:2; D_3: Basal fertilizer: Tiller fertilizer: Spike fertilize = 6:3:1), a total of 12 treatments using completely randomized trials are detailed in Table 1.

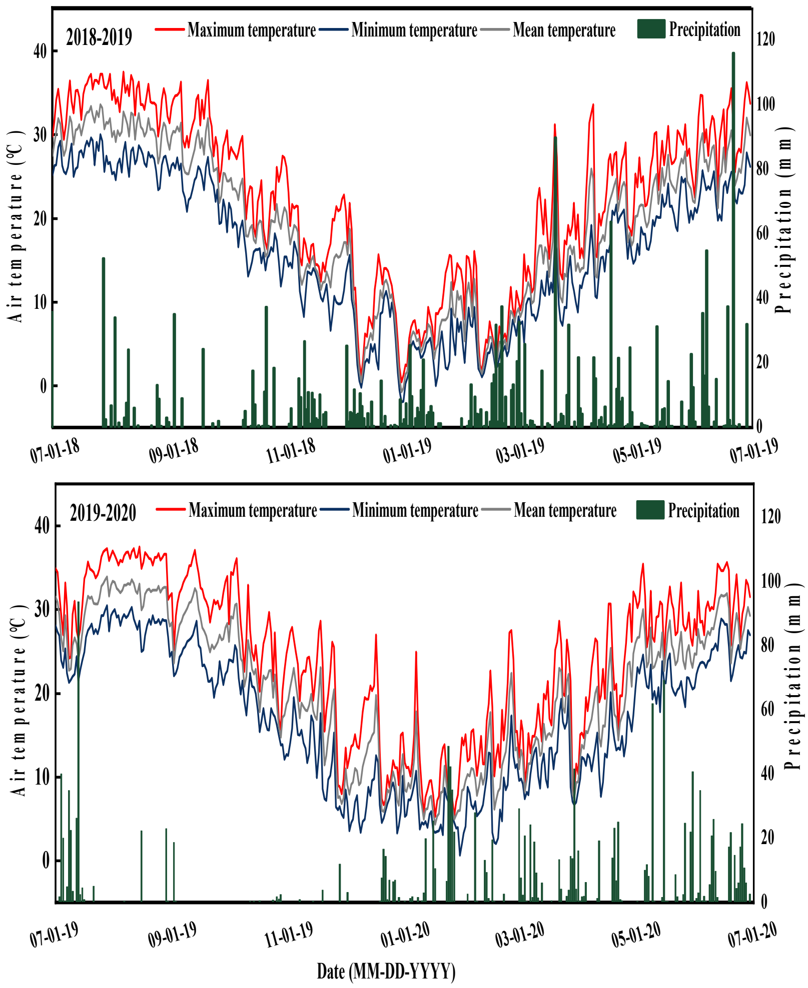

Figure 2. Precipitation and air temperature during the double-harvest rice growing seasons.

Table 1. Fertilization treatment of early rice nitrogen fertilizer management experiment.

Treatment	B			T	S
	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	N (kg ha^{-1})	N (kg ha^{-1})
F_1D_1	37.5	75	112.5	12.5	0
F_2D_1	75	75	112.5	25	0
F_3D_1	112.5	75	112.5	37.5	0
F_4D_1	150	75	112.5	50	0
F_1D_2	25	75	112.5	15	10
F_2D_2	50	75	112.5	30	20
F_3D_2	75	75	112.5	45	30
F_4D_2	100	75	112.5	60	40
F_1D_3	30	75	112.5	15	5
F_2D_3	60	75	112.5	30	10
F_3D_3	90	75	112.5	45	15
F_4D_3	120	75	112.5	60	20
CK	0	75	112.5	0	0

Note: B represents basal fertilizer, T represents tiller fertilizer, and S represents spike fertilize.

Except for the early rice experiment, fertilization was applied twice in other years. The base fertilizer was compound fertilizer (N 112.5 kg ha^{-1}, P_2O_5 112.5 kg ha^{-1}, and K_2SO_4 112.5 kg ha^{-1}). The application of urea as nitrogen fertilizer at the tillering stage, the nitrogen application rate of early rice was 52 kg ha^{-1}, and that of late rice was 62 kg ha^{-1}, which refers to the fertilizer application standard of local double-harvest rice production. The irrigation amount during the growth period of double-harvest rice is determined according to its needs, and pesticide and weeding measures are consistent with the local. The physical and chemical properties of topsoil were measured before the sowing of double-harvest rice. The growth of double-harvest rice was observed and recorded at each growth period, and the measured yield was after maturity.

2.3. Model Simulation

The experimental data of our study include late rice data in 2018, double-harvest rice data in 2019 and early rice data in 2020. The parameter calibration of the DSSAT model uses late rice data in 2018 and early rice data in 2019. The parameter validation of the DSSAT model uses late rice data in 2019, and early rice data in 2020.

2.3.1. CERES-Rice Model

The CERES-Rice model used in this paper is a rice sub-model of the CERES (Crop-environment resource synthesis) in the DSSAT (Agricultural Technology Transfer Decision Support System). Using the CERES-Rice model, not only the effects of conventional soil conditions, climatic conditions, genetic types, and crop management on rice growth and yield can be accomplished, but also multi-objective optimal management decisions can be achieved [24], providing users with adaptive field management methods that efficiently utilize natural resources and avoid natural disasters [25,26]. Due to the strong adaptability and simulation ability of the CERES-Rice model, scholars at home and abroad have done a lot of research on its application in agriculture, such as predicting rice yield, simulating water and nitrogen balance and adaptive coping strategies [27,28].

The CERES-Rice model is a special model for rice simulation in the DSSAT model. The simulation of the crop-growth process is carried out on a daily scale. It simulates the phenological growth process of rice from sowing to harvest under different management modes, crop photosynthesis, dry matter distribution of roots, stems and leaves, and final crop yield. At the same time, it can also simulate the water and N balance of rice growth period [29,30]. The DSSAT model consists of five modules: database, model sub-module, application analysis module, backup software, and user interface. The structure of the model is shown in Figure 3.

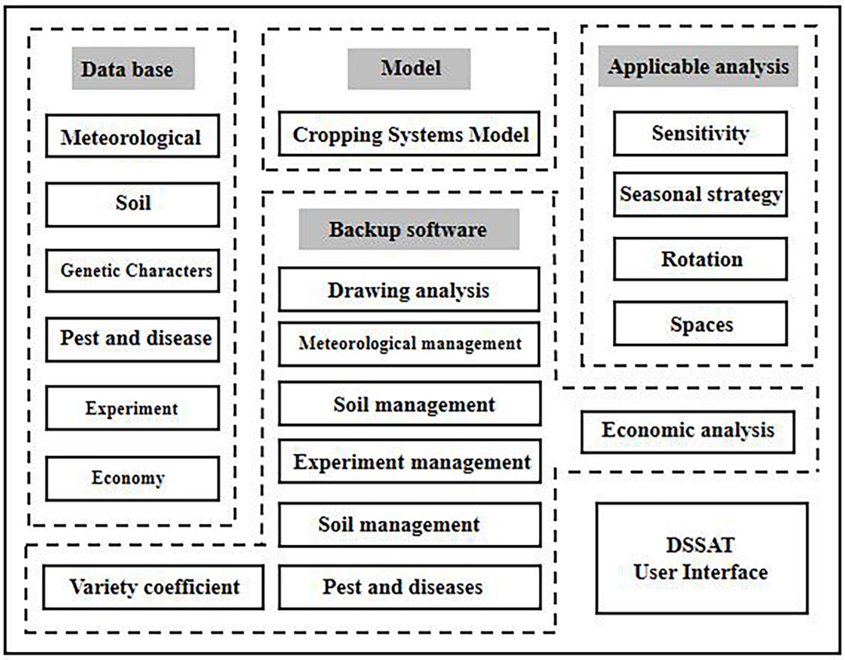

Figure 3. Diagram of database application and support software components of DSSAT.

2.3.2. Model Input Data

(1) Meteorological data

The historical meteorological data of the study area and the meteorological data during the experiment were downloaded from the China Meteorological Data Network (http://data.cma.cn/, accessed on 20 October 2020). The meteorological data input in the model are daily average meteorological data, including solar radiation, rainfall, daily maximum temperature, and daily minimum temperature.

(2) Soil data

The soil data to be input into the model include: soil properties, mechanical composition, organic carbon and other nutrients, soil drainage rate, bulk density, etc. The soil data in this study are derived from the actual measurement of the field experiment and the empirical data are automatically generated by some models.

(3) Field management data

During the experiment, field management data were collected according to the needs of the model and its own research direction, including planting varieties, planting methods and density, sowing date, flowering period, maturity period, irrigation, and fertilization.

(4) Crop data

The minimum data input acceptable to the model is the sowing date, flowering stage, maturity stage, and yield. In addition, there are above-ground biomass, leaf area index, etc., in each period of the rice growth period, as well as yield components during yield measurement.

In the process of the CERES-Rice model simulating rice production, eight genetic characteristic parameters were set to describe the growth status of rice, including P1, P2R, P5, and P2O, which described the basic growth period, and G1, G2, G3, and G4, which had a direct impact on rice yield and organ formation. The meaning and range of each parameter [29] are shown in Table 2.

Table 2. Calibrated genetic coefficient values for double-harvest rice.

Parameters	Meaning	Value Range	Xiang Early-Indica45	Ganwan37
P1 (°C.d)	Time period or basic vegetative phase	210–900	211.8	255.4
P2R (°C.d)	Photoperiodism coefficients	30–200	31.70	71.77
P5 (°C.d)	Grain filling duration coefficient	330–550	521.1	333.9
P2O (h)	Critical photo-period	104–130	12.4	12.6
G1	Spikelet number coefficient	20–80	77.7	78.5
G2 (g)	Single grain weight	0.02–0.03	0.20	0.21
G3	Tiller coefficients	0.3–1	0.51	0.43
G4	Temperature tolerance coefficient	0.8–1.25	1.06	1.16

2.3.3. Determination of Genetic Parameters of Double-Harvest Rice

In this study, the GLUE parameter adjustment tool in the DSSAT model was used to determine the genetic parameters of early rice and late rice by the ‘trial and error’ method. The model was established by using the data of late rice in 2018 and early rice in 2019 as the model simulation file, and the model was established by using the experimental data from late rice in 2019 and early rice in 2020 as the verification file. In this study, the final genetic parameters of early rice ‘Xiang early-indica45’ and late rice ‘Ganwan37’ were determined as follows (Table 2).

2.3.4. Model Performance Statistics

As has been demonstrated by a number of previous studies [31,32], the statistical indices used to evaluate the relative difference between the simulated and measured values were coefficient of determination (R^2, Equation (1)), root mean square error (RMSE, Equation (2)), and normalized root means square error (n-RMSE, Equation (3)).

The formulae of these statistic indices are as follows [33]

$$R^2 = \frac{\left[\sum_{i=1}^{n}(m_i - \overline{m}) \times (s_i - \overline{s})\right]^2}{\sum_{i=1}^{n}(m_i - \overline{m})^2 \times \sum_{i-1}^{n}(s_i - \overline{s})^2} \quad (1)$$

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(s_i - m_i)^2}{n}} \quad (2)$$

$$\text{n-RMSE} = \frac{\text{RMSE}}{\overline{m_i}} \times 100 \quad (3)$$

where s_i = Simulated value; $\overline{s}$ = Average of simulated values in date set; m_i = measured value; $\overline{m_i}$ = Average of measured values in date set; n = total number of samples.

The coefficient of determination (R^2) is the statistic to measure the goodness of fit, the closer R^2 is to 1, the closer the simulation result is to the measured value, and the higher the simulation accuracy is. The Root Mean Square Error (RMSE) summarizes the average difference between simulated and observed values, and normalized Root Mean Square Error (n-RMSE) shows the relative size of the average difference without units. In this study, we consider n-RMSE < 10% as "excellent" agreement; 10% ≤ n-RMSE < 20% as "good" agreement; 20% ≤ n-RMSE < 30% as "moderate" agreement; and n-RMSE ≥ 30% as "poor" agreement.

2.4. Climate Generation Model

The down-scaling method used in this paper is proposed by Professor Liu Deli from the Wagga Institute of Agriculture, Department of Primary Industries, New South Wales, Australia. The down-scaling method is used to downscale the future climate data of four stations around Nanchang City of CMIP5 under the RCP4.5 emission model to obtain the future daily climate data of Nanchang City. The spatial down-scaling uses the inverse weight interpolation method (IDW) to convert the monthly raster data into site data. The calculation formula is as follows:

$$S_i = \sum_{k=1}^{4}\left[\frac{1}{d_{i,k}^m}\left(\sum_{j=1}^{4}\frac{1}{d_{i,k}^m}\right)^{-1} P_k\right] \quad (4)$$

where: S_i is the down-scaled data of site i; P_k is the GCM prediction value of grid unit k; d_i, k is the center distance between site i and grid unit, m is the control reference, and its common value is m = 3 [34].

After using the above formula to generate the required site data, the qq-mapping deviation correction method is used to correct the data to ensure the fitting degree between the simulated data and the observed data and improve the simulation accuracy. The calculation formula is as follows:

$$x_k^f = y_i^o + \frac{y_{i+1}^o - y_i^o}{x_{i+1}^h - x_i^h}\left(x_k^r - x_i^h\right) \; x_i^h \le x_k^r \le x_{i+1}^h \quad (5)$$

where: x_k^f(k = 1, 2, ... , n) is the corrected GCM climate prediction value; $x_i{}^h$ is the monthly GCM data of the evaluation period; x_i^h is the future GCM climate prediction value (before bias correction); y_i^o is the monthly observation data of the site during the evaluation period.

After obtaining the corrected monthly meteorological data in the future study area, the station data is down-scaled by the modified WEGN weather random generator to obtain daily meteorological data. Taking rainfall as an example, the calculation formula is as follows:

$$\mathrm{f}(p) = \frac{p^{\alpha-1}e^{\frac{-p}{\beta}}}{\beta^{\alpha}\tau(\alpha)} \quad p,\ \beta > 0, 0 < \alpha < 1 \tag{6}$$

where: p is the monthly rainfall data, the α and β values of each station are the model-driven parameters, which are determined by the linear function relationship between the corresponding GCM monthly average precipitation data and the parameters.

The meteorological data used in the article include the BCC-CSM1-1, BCC-CSM1-1m, and BN-ESM climate generation models provided by the National Meteorological Center (represented by BC1, BC2, and BNU, respectively). The daily meteorological data of 2021–2070 in Nanchang City under the RCP4.5 path includes daily precipitation, daily solar radiation, daily maximum temperature, and daily minimum temperature. The climate down-scaling data in this paper are provided by Professor Liu Deli's research team from the Department of Primary Industries (Department of Agriculture), New South Wales, Australia.

3. Results

3.1. Calibration and Validation of the CERES-Rice Model

The results of the field experiment showed that the suitable nitrogen application rates for early rice and late rice in the Nanchang area were 100 kg/ha and 150 kg/ha, respectively, and the CEREs-Rice model was calibrated and validated under this nitrogen level. As shown in Table 3, the CERES-Rice model after calibration and verification has a good simulation of double-harvest rice. Except for the n-RMSE of flowering stage simulation in late rice simulation in 2019 which was 11.67%, the n-RMSE of other models was less than 10%. The model works well in simulating yield, which provides a reliable practical basis for the later application to the simulation of double-harvest rice yield in Nanchang under future climate scenarios. In the simulation of late rice in 2019, the simulation of the phenological period is better, which can provide a reference for the model simulation, but to a certain extent, the simulation effect error may be larger due to the error. This problem should be considered in the later research on early sowing dates.

Table 3. Relationship between observed and simulated yield and phenophase of double-harvest rice.

Experiment	Treatments	Yield(kg/ha)			Flowering Period(d)			Maturation Period(d)		
		Simulated	Measured	n-RMSE	Simulated	Measured	n-RMSE	Simulated	Measured	n-RMSE
Calibrated late rice (2018)	1	8210	8210	0.110%	61	62	1.610%	100	95	5.260%
Calibrated early rice (2019)	1	6832	6852	3.050%	71	70	1.000%	106	100	6.000%
	2	7433	7127		71	71		106	100	
	3	6688	6638		71	70		106	100	
	4	7368	7088		71	71		106	100	
	5	6699	6704		71	70		106	100	
	6	7432	7127		71	71		106	100	
Validated late rice (2019)	1	7500	7500	3.750%	67	60	11.670%	103	94	9.570%
Validated early rice (2020)	1	5380	5972	9.910%	70	71	1.430%	103	102	0.980%

3.2. Climate Down-Scaling Model

3.2.1. Down-Scaling Data Quality Control

The historical (2001–2010) down-scaling climate data under the RCP4.5 emission path generated by the model and the historical data measured by the meteorological station were analyzed and studied. For the meteorological factors with poor model simulation, the linear relationship was used to correct the deviation of the simulated meteorological data. After correction, the simulation results of daily maximum temperature, daily minimum temperature, and solar radiation are evaluated by the measured and simulated meteorological data in 2005. If the simulation results become worse after correction, the model will be used to generate data.

(1) Analysis of precipitation simulation effect

As shown in Figure 4, the measured and simulated daily precipitation data from 2001 to 2010 are selected for analysis. The daily precipitation distribution under the three models is concentrated in the spring and summer of each year. The annual distribution of simulated daily precipitation is generally consistent with that of measured daily precipitation, and the precipitation period is concentrated in the rainy months. In the analysis of annual precipitation (Figure 5), in the comparison between the simulated and the measured value of the total annual precipitation from 2001 to 2010, the inter-annual variation of the measured annual precipitation simulated by the three models. The changing trend of annual precipitation was simulated by BC2 is the most consistent with the measured data, and the correlation is the best. The other two models have poor simulation results in 2001–2005, and the simulation effect in the next five years is acceptable. The distribution of natural precipitation has great randomness. The law of multi-year climate may be consistent in a certain period of time, but the daily precipitation will continue to change randomly. Therefore, the precipitation data is based on the BC2 model simulation data as the final data, and no deviation correction is performed.

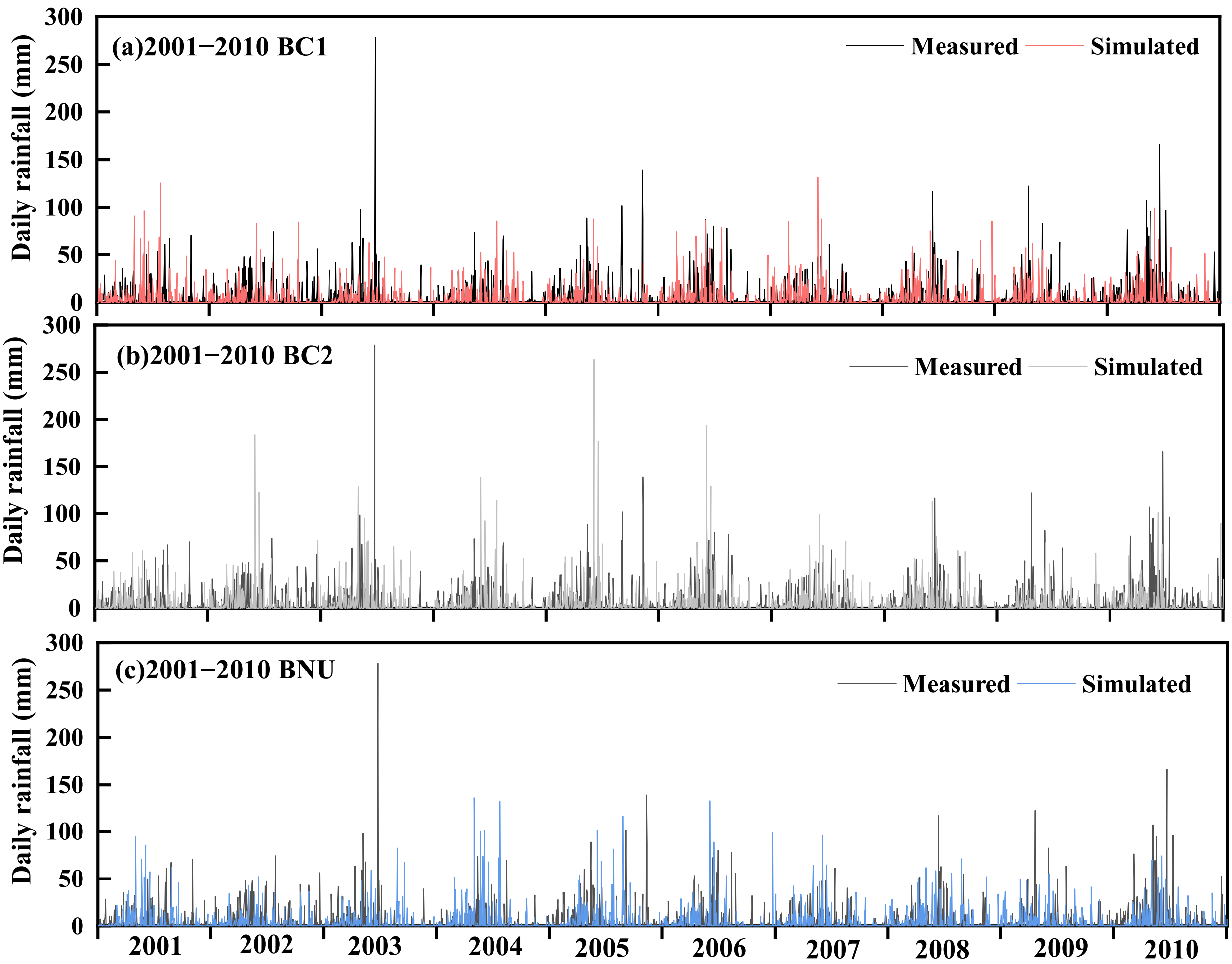

Figure 4. Comparison of measured and simulated daily precipitation from 2001 to 2010.

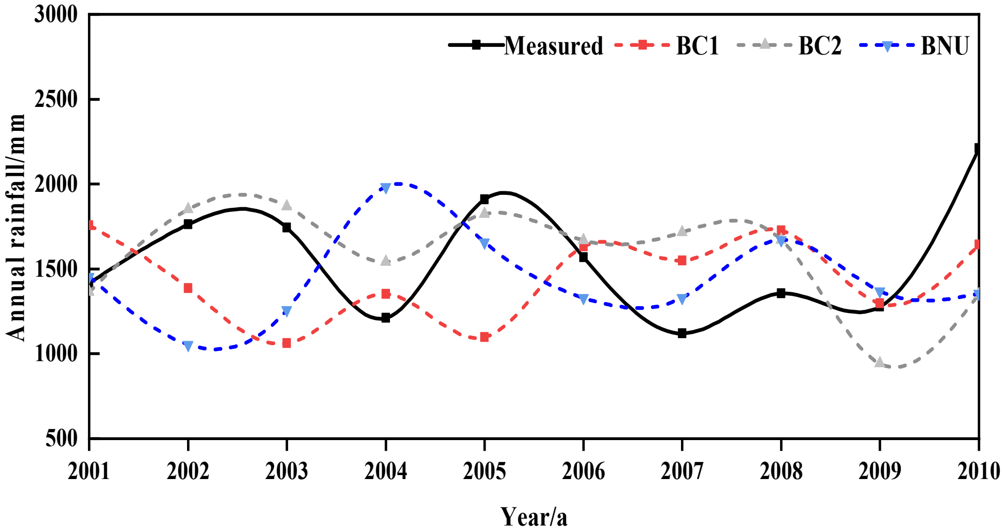

Figure 5. Comparison of measured and simulated precipitation values from 2001 to 2010.

(2) Analysis temperature simulation effect

The simulation results of the three models for the daily maximum temperature (2005) are basically consistent with the distribution of measured data (Figure 6). For the simulation of the whole year, the R^2 between the simulated and measured data of the three models (BC1, BC2, BNU) are 0.834, 0.865, and 0.836, respectively, and the BC2 model has the highest correlation. In the daily maximum temperature simulation from January to February, the three models showed that the simulated values were higher than the measured values, and the deviation of the BNU model was the largest, followed by BC1; in the simulation of the daily maximum temperature distribution in the high-temperature period of one year, the BC1 and BC2 models perform better than BNU. In the analysis of the daily maximum temperature in the selected year, the simulation effect of the BC2 model was the best. Through the deviation correction comparison, after the model prediction data is corrected, the fitting degree between the simulated value and the measured value is lower than that before the correction, and the BNU deviation is the largest, so the daily maximum temperature is not corrected. The daily maximum temperature is based on the BC2 model simulation data as the final climate input selection.

The simulation and measurement results of the daily minimum temperature are shown in Figure 6. The change of daily minimum temperature has a great influence on the growth of double-harvest rice. In the physiological growth period, it may lead to the growth of crops to slow down or stop. In the reproductive growth period, a low temperature will cause rice production to decrease. A temperature too low will cause damage to the physiological function of crops, resulting in reduced or even no harvest. The correlation coefficients (BC1, BC2, BNU) between the simulated and measured values of the three models for the minimum temperature were 0.913, 0.925, and 0.894, respectively. In the minimum temperature simulation from January to February, there was no significant difference in the simulation results of the three models. The change of temperature in this period would affect the accumulation of accumulated temperature and the sowing date of early rice. In April and July (day sequence 90–200 d) of early rice-sowing season, the change of minimum temperature may delay the sowing date, while the simulated values of the three models are basically consistent with the measured values, and there is no significant difference between the model simulation results. In general, the simulation results of the three models are acceptable and the simulation results of the three models can be considered as the final input meteorological data, and the deviation correction of the simulation value is no longer carried out.

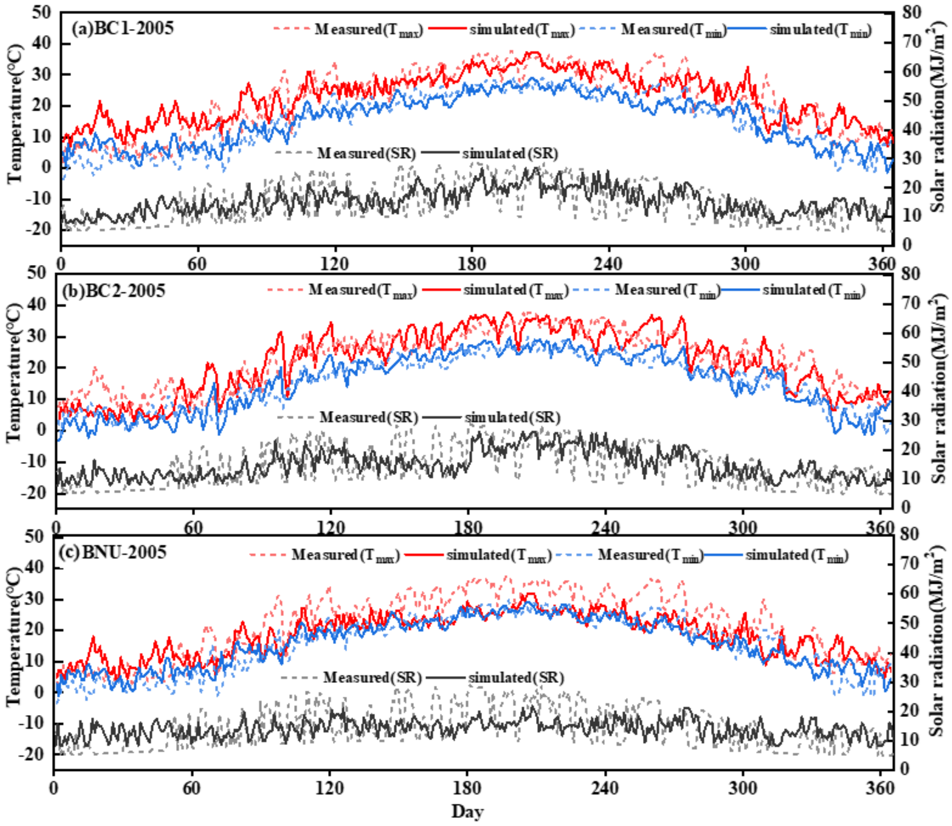

Figure 6. Comparison of measured and simulated daily solar radiation and temperature values in 2005.

(3) Analysis of solar radiation simulation effect

The simulation results of the solar radiation simulation data are shown in Figure 6. The R^2 between the simulated values of solar radiation and the measured values under the three models (BC1, BC2, BNU) is 0.317, 0.542, and 0.553, respectively. The correlation coefficient is the highest in BNU, but it does not exceed 0.6. The simulation effect of the BNU model is the worst, and the simulation value is lower than the measured value. The simulation effect of the BC1 and BC2 models is better in the second half of the year, the simulation effect of the BC1 model is worse in the maximum value of daily solar radiation between 120–200 d, and the simulation effect of the BC2 model is worse in the maximum value of daily solar radiation between 50–180 d, and the simulation effect is worst between 150–180 d. The BC1 model simulation data fitting effect is better, followed by the BC2 model, and the BNU model simulation effect is the worst.

Based on the above research on the simulation effect of precipitation, daily maximum temperature, daily minimum temperature and solar radiation, the BC2 model is selected as the meteorological input file of the DSSAT -CERES-Rice model.

3.2.2. Future Climate Prediction in Nanchang

The future annual precipitation and solar radiation changes in Nanchang are shown in Table 4 (baseline year: 1961–2015). The annual precipitation change shows an increasing trend, but before 2038, the precipitation is lower than the base year precipitation. By 2070, the annual rainfall will increase by 6.16%. In the future, the average daily solar radiation value will show a slow increase trend, and the simulated solar radiation value is higher than the average measured value in the baseline year during the forecast period. The temperature will increase in the future (Figure 7), and the daily maximum temperature increase in 2035 was 1.33 °C, and will increase by 1.64 °C in 2050. In 2070, the daily maximum temperature increased by 2.06 °C (Table 4). Rising temperatures may bring more uncertainty to crop production, and the frequency of climate disasters increases.

Table 4. Future Changes of Temperature, Rainfall, and Solar Radiation in Nanchang.

Year/a	RCP4.5						
	T_{max}/°C	T_{av}/°C	T_{min}/°C	Annual Rainfall/mm	Δ%	Solar Radiation/MJ·m^{-2}	Δ%
Baseline year	21.95	18.45	14.95	1595.83	0	14.79	0
2035s	1.33	1.08	0.82	1567.22	−1.79	14.95	1.09
2050s	1.64	1.38	1.12	1608.67	0.80	15.09	2.06
2070s	2.06	1.79	1.52	1663.93	4.27	15.29	3.36

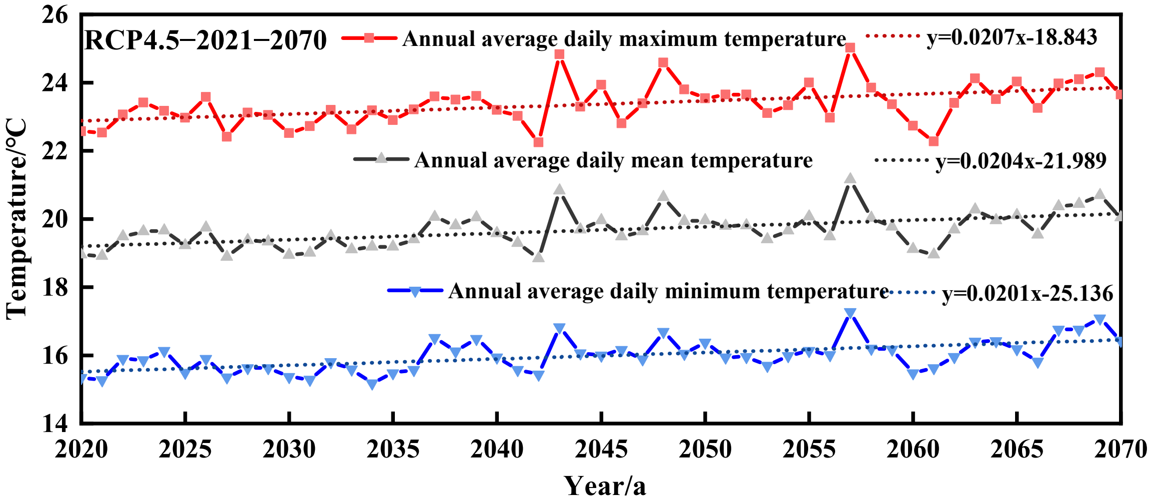

Figure 7. Forecast future meteorological temperature in Nanchang.

3.3. Effects of Future Climate Change on Double-Harvest Rice Yield in Nanchang

3.3.1. Phenological Period and Yield Changes of Early Rice under Future Climatic Conditions

Under the RCP4.5 emission scenario, the simulation of rice phenology and yield changes in Nanchang is shown in Table 5. The yield of early rice in the next three time periods shows an increasing trend over time, but it is lower than the base year (1986–2015). The yield of early rice in 2035 was 3709 kg/ha, and in 2070 reached 4818 kg/ha (6.79% lower than the base year). The days required for flowering and the whole growth period of early rice showed a decreasing trend, but the whole growth period of early rice was always greater than the experimental year.

The attribution analysis of the future early rice yield in Nanchang under the RCP4.5 emission scenario shows that the future early rice yield is lower than the experimental year, and the yield change increases slowly with the year, which may be related to the precipitation during the early rice growth period (Table 5). In addition, the increase in solar radiation, daily minimum temperature and daily maximum temperature also laid a foundation for the slow increase in early rice yield. The number of days in the whole growth period of early rice increased first and then decreased, which may be related to the decrease in precipitation, the increase in solar radiation and temperature. Under the RCP4.5 scenario, the yield of early rice was lower than that of the experimental year, which may be caused by the change of precipitation below the experimental year, and the increase in solar radiation and temperature provided the basis for the recovery of early rice yield. The most likely reason for the change of the number of days in the whole growth period of early rice is the combined effect of lower precipitation than the experimental year and slow recovery in the later period.

Table 5. Changes in precipitation, solar radiation, temperature, phenological period, and yield in double-harvest rice growing period in Nanchang.

Time (a)	Meteorological Indexes		1986–2015	2035	2050	2070
Early rice	Rainfall (mm)	Growth period	1050.5	895.1	900.2	906.9
		Δ%	0	−14.8	−14.3	−13.7
	Solar radiation (MJ/m^2)	Growth period	15.4	15.5	16.0	16.6
		Δ%	0	0.6	3.7	7.9
	Daily maximum T (°C)	Growth period	27.9	28.3	28.6	29.1
		Δ%	0	1.3	2.6	4.2
	Daily minimum T (°C)	Growth period	20.7	21.0	21.0	21.1
		Δ%	0	1.5	1.6	1.7
	Days from sowing to flowering (d)		70	71	70	69
	Days of whole growth period (d)		100	105	104	102
	Yield (kg/ha)		5169	3709	4184	4818
Late rice	Rainfall (mm)	Growth period	206	261.7	274.2	290.8
		Δ%	0	27.1	33.1	41.1
	Solar radiation (MJ/m^2)	Growth period	18.6	15.9	16.1	16.5
		Δ%	0	−14.6	-13.2	−11.3
	Daily maximum T (°C)	Growth period	30.7	30.0	30.2	30.5
		Δ%	0	-2.4	−1.7	−0.8
	Daily minimum T (°C)	Growth period	23.0	22.2	22.4	22.7
		Δ%	0	−3.5	−2.5	−1.1
	Days from sowing to flowering (d)		59	63	63	62
	Days of whole growth period (d)		95	98	97	95
	Yield (kg/ha)		6642	5713	5760	5823

3.3.2. Phenological Period and Yield Changes of Late Rice under Future Climatic Conditions

Under the RCP4.5 emission scenario, the simulation of rice phenology and yield changes in Nanchang is shown in Table 5. In the future, the yield of late rice in Nanchang is lower than that in the experimental year, and the yield of late rice increases slightly with time. In 2070, the yield of late rice is still 12.33% lower than that in the base year, and the number of days required for flowering does not change much.

The attribution analysis of the phenological period, yield change and climate change of late rice in the future shows that the yield of late rice is lower than that of the experimental year, which may be caused by the lower solar radiation and temperature than the experimental year (Table 5). The reduction in lower temperature and solar radiation may delay crop growth, reduce its photosynthetic efficiency, and affect the final yield of late rice. With the slow increase in solar radiation and temperature, rice yield also began to rise, and it also explained the changing trend of the number of days in the whole growth period from greater than the experimental year to slow down.

The future yield of double-harvest rice in the Nanchang area is lower than that in the experimental year, and the yield reduction of early rice is more obvious, but the yield of double-harvest rice increases with time. In the process of early rice growth, the biggest meteorological factor affecting the change of early rice yield in the future is the decrease in precipitation. The increase in temperature provides an environmental basis for the slow recovery of yield, and the decrease in precipitation and solar radiation provides the possibility for the extension of the whole growth period of early rice. During the growth and development of late rice, solar radiation and daily maximum temperature and daily minimum temperature lower than the test year may be the important reasons for the lower yield of late rice in the future than the yield of late rice in the test year, the number of flowering days and the number of days in the whole growth period. The recovery of three meteorological factors over time also caused the slow increase in late rice yield and the shortening of the phenophase period.

3.4. Adaptability Strategy of Double-Harvest Rice Production to Climate Change

3.4.1. Effects of Different N Application Ratios on Double-Harvest Rice Yield under Future Climate

The conventional nitrogen application ratios B:T = 3:1 (as the application mode before adjustment) was changed to the fertilization ratios B:T:S= 5:3:2 and B:T:S = 6:3:1. The effects of changing nitrogen application ratios on the yield and phenological period of early rice in Nanchang are shown in Table 6. When the nitrogen-application ratio was adjusted to 5:3:2, it could promote the yield of early rice under the RCP4.5 scenario. Compared with the yield before adjustment, the increase in yield showed a decreasing trend with time. The results showed that the nitrogen application ratios of 5:3:2 promoted the yield of early rice. In the later stage of the experiment, the promotion effect gradually decreased due to climate change. With the adjustment of the nitrogen application ratio, the phenological period of early rice increased with time, which was opposite to that before the adjustment. When the nitrogen application ratio was adjusted to 6:3:1, the adjustment of nitrogen fertilizer ratios before 2050 had a positive effect on the yield of early rice, while the yield of early rice after adjustment in 2070 was lower than that before the adjustment. The number of days in the whole growth period showed an opposite trend before and after adjustment. The adjustment of nitrogen fertilizer ratios would prolong the growth period of early rice and increase the yield. Under the two different nitrogen application ratios, the phenophase of early rice was prolonged, and the nitrogen application ratio of 5:3:2 was the best.

Table 6. Future changes of double-harvest rice yield and phenological period in Nanchang under the different nitrogen application ratio.

Variety	Phenological Period and Yield	5:3:2			6:3:1		
		2035	2050	2070	2035	2050	2070
Early rice	Flowering period before adjustment/d	71	70	69	71	70	69
	Flowering period after adjustment/d	70	70	71	70	70	71
	Whole growth period before adjustment/d	105	104	102	105	104	102
	Whole growth period after adjustment/d	103	104	105	103	104	105
	Yield before adjustment/kg/ha	3709	4184	4818	3709	4184	4818
	Yield after adjustment/kg/ha	4342	4564	4860	4034	4314	4686
Late rice	Flowering period before adjustment/d	63	63	62	63	63	62
	Flowering period after adjustment/d	63	63	62	63	63	63
	Whole growth period before adjustment/d	98	97	95	98	97	95
	Whole growth period after adjustment/d	99	97	96	98	97	96
	Yield before adjustment/kg/ha	5713	5760	5823	5713	5760	5823
	Yield after adjustment/kg/ha	5609	5787	6024	5609	5787	6024

The effects of changing the proportion of nitrogen fertilizer application on the yield and phenological period of late rice in Nanchang are shown in Table 6. The yield of late rice showed a trend of decreasing first and then increasing. After 2050, the adjusted yield was higher than that before the adjustment, and increased with time. There was no significant change in the phenological period.

3.4.2. Effect of Changing Sowing Date on Yield of Double-Harvest Rice under Future Climate

In this study, the RCP4.5 emission scenarios were selected as the future climate change scenario in Nanchang, and the effect of changing the sowing date of double-harvest rice on its yield was studied. The sowing dates were changed to 20, 15, 10, 5 days in advance and 5, 10, 15 days in delayed sowing. The nitrogen application ratio of B:T:S = 5:3:2 was selected. The yield of double-harvest rice before the sowing date was adjusted as the benchmark to study the yield change.

As shown in Figure 8, in the next three periods, changing the sowing date can change the final yield of early rice to some extent. From 2021 to 2035, the treatment of 15 days in advance could increase the yield of early rice to the greatest extent (53.54% higher than that before adjustment), while the yield would decrease when it was delayed by 15 days or more. From 2035 to 2050, an early sowing date can increase the yield of early rice, but a delay will cause the yield reduction in early rice. Among them, the best sowing date is 10 days in advance (35.59% higher than that before adjustment); from 2050 to 2070, an early sowing date will lead to early rice yield reduction, and delay will lead to an early rice yield increase. Among them, the yield of the late sowing date 15 days is the best (27.70% higher than that before adjustment).

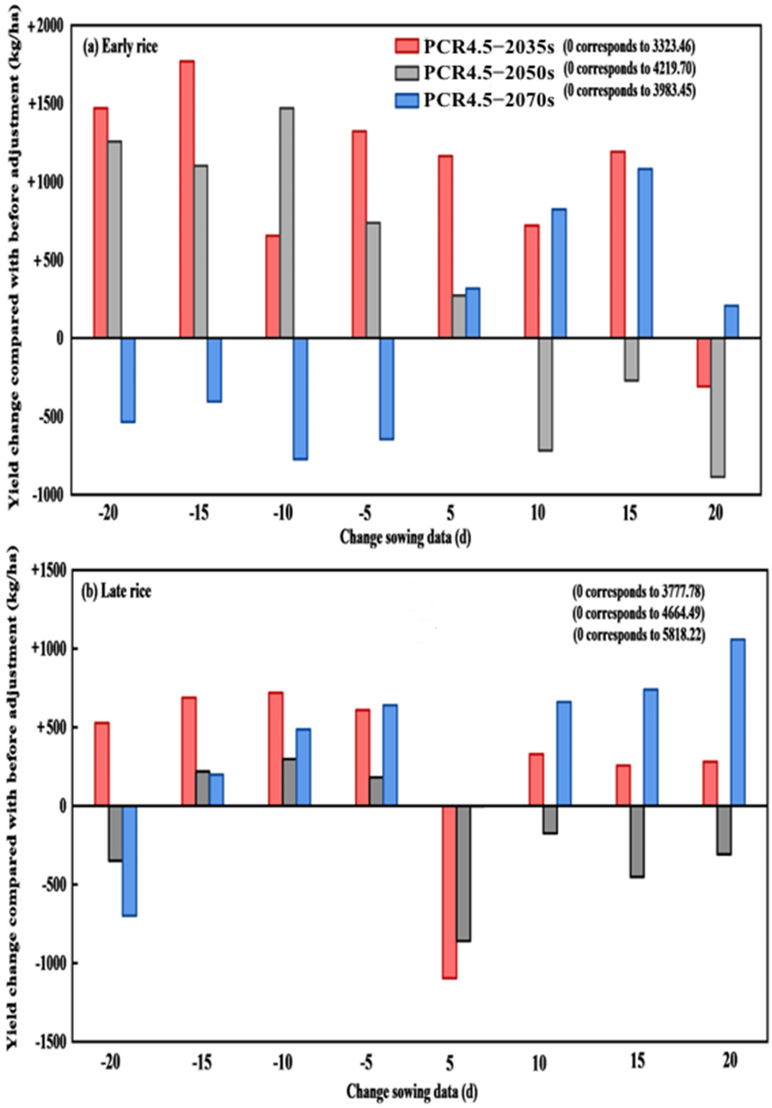

Figure 8. The effect of changing the sowing date of double-harvest rice on its yield.

In 2021–2035, the highest increase in yield was achieved by 10 days in advance (19.24% higher than that before adjustment), and a delay of 5 days will cause a decrease in yield. From 2035 to 3050, an early sowing date can increase the yield of late rice to a certain extent, but the increase is not obvious. Delaying the sowing date will cause yield reduction, and the highest yield is obtained by 10 days ahead of the sowing date (6.47% higher than that before adjustment). From 2050 to 2070, when the sowing date was 5 days in advance or delayed by 10 days or more, the yield of late rice could increase, and the best sowing date was delayed by 20 days (13.29% higher than that before adjustment), and the other would reduce the yield, but the delayed sowing date was too long, which might cause the late rice to suffer from low temperature and freezing injury in the later stage of late rice growth.

Double-harvest rice sowing as a whole will be affected by each other, so we also need to consider the coordination of double-harvest rice sowing mechanism. Therefore, in 2021–2035, the optimal yield of rice can be obtained by sowing early rice about 15 days in advance and sowing late rice about 10 days in advance. From 2035 to 2050, early rice and late rice were sown about 10 days in advance, and a higher total yield of double-cropping rice would be obtained. In 2050–2070, the total yield of double-cropping rice is likely to be optimal with a delayed sowing date of 10–15 days.

4. Discussion

Based on the experimental data and meteorological data of double-cropping rice carried out in the Nanchang area from 2018 to 2020, the DSSAT-CERES-Rice model was established, and the genetic parameters of two conventionally used early and late rice varieties were simulated and verified. Based on the GCM down-scaling data of RCP4.5 in the next 50 years (2021–2070), the effect of future climate change on the yield of double-harvest rice in Nanchang was predicted by using the validated model. The effects of changing the sowing date of double-harvest rice and nitrogen fertilizer application ratios on the production of double-harvest rice in Nanchang in the future were simulated, and the adaptive coping strategies of double-harvest rice production under the possible future climate were put forward.

In the process of using experimental data to simulate and verify the rice model, the CERES-Rice model has achieved good simulation and verification results for the experimental model based on experimental data. The verified model has high simulation accuracy in simulating the phenological period and yield of double-harvest rice, which provided a model basis to simulate different treatments for future double-harvest rice production. Based on the experimental data, the crop model is simulated and verified, and then the CERES-Rice model verified by the experimental data is used to simulate the rice production in the study area. It has been applied by many scholars and will become a mainstream research direction in future agricultural research. Compared with the traditional field experiment, crop model simulation has many advantages, such as convenient, fast, and low input cost [34]. It is the inevitable direction of development in today's society with the sustainable development of science and technology. However, the model simulation also has its shortcomings. The best crop model today cannot carry out detailed and comprehensive simulations of crop growth. The basis of its establishment is a relatively reasonable hypothesis. The model is constructed with the theoretical knowledge that can be understood at this stage. The future development of crop models still needs to invest more research work. The research in this paper can provide research reference cases to a certain extent.

Through the validation of simulation results, the meteorological data simulated by the BC2 model were selected as the assumption of future meteorological changes in Nanchang. In the BC2 model, the trend of temperature increase and rainfall increase in Nanchang in the future is consistent with the research trends of Lu Xianghui [17]. Through the follow-up analysis of the yield and phenological period of double-harvest rice in Nanchang under the RCP4.5 scenario, the largest meteorological factor affecting the yield change may be the decrease in precipitation during the growth of early rice. Under the RCP4.5 and RCP8.5 climate scenarios of Boonwichai S et al. [35], based on the DSSAT model, the irrigation water demand, rice yield and crop water productivity of Thai jasmine rice were studied. The effect of rainfall on future rice yield may be greater than the effect of temperature. The decrease in rainfall and the increase in temperature will increase the amount of irrigation water. In 2080, the yield of rice will decrease by 14% and 10% in the two climate scenarios, respectively, which is consistent with the decrease in early rice yield in this study. At the same time, under the RCP4.5 scenario, the increase in temperature provides an environmental basis for the slow recovery of yield, and the decrease in precipitation and solar radiation provides the possibility for the extension of the whole growth period of early rice. During the growth and development of late rice, solar radiation and daily maximum temperature, daily minimum temperature lower than the experimental year may be an important reason for the lower yield of late rice under the RCP4.5 scenario than the yield of late rice in the experimental year, the number of days of flowering and the number of days of the whole growth period. The recovery of three meteorological factors over time also brought a slow increase in late rice yield and a shortening of the phenological period.

The adjustment of the nitrogen application ratio has a positive effect on the yield of early rice. The yield of early rice after adjustment is generally greater than that before adjustment. The phenological period extends with time, but the yield varies with time. As a whole, the nitrogen application ratio of 5:3:2 had the best yield effect. Increasing nitrogen fertilizer at the panicle stage was beneficial to the increase in rice yield, which was consistent with the research results of Li [36]. The response of late rice to the nitrogen application ratio was obvious only after 2050, and the effect was less than that of early rice. Changing the sowing date can effectively change the yield of double-harvest rice, which is consistent with the research results of Chuang Liu [37] and Hu Lei [38]. Delaying the early sowing date can effectively increase rice yield, but the application degree of the measures needs to be considered in combination with the consideration of double-cropping rice as a whole. Early or delayed early rice sowing dates should be combined with the change of late rice sowing date. To sum up, the reasonable change of double-harvest rice-sowing date and early rice nitrogen management may become important strategies to deal with future climate change.

This work has not been carried out in the actual experiment. Therefore, the mechanism simulation of its actual production may not be very accurate. It can be used as a reference for the agricultural guidance department in Nanchang, and its effect on the production practice of double-cropping rice remains to be verified.

5. Conclusions

(1) After modeling and validation, the DSSAT-CERES-Rice model can be well applied to simulate the double-harvest rice production in Nanchang.
(2) Compared with the base year (1961–2015), the future average annual precipitation shows an increasing trend, and its value will be higher than the base year after 2036, while the daily maximum and minimum temperature showed an increasing trend, but the solar radiation was lower than the average of the base year.
(3) Under the RCP4.5 scenario, the future yield of double-harvest rice in the Nanchang area was lower than that in the experimental year, and the yield reduction in early rice was more obvious. The yield of early rice and late rice increased with time, but the yield of early rice and late rice in 2070 was still reduced by 24.25% and 24.47%, respectively.
(4) Adjusting the proportion of nitrogen application had a positive effect on the yield of early rice. Under the RCP4.5 scenario, the best treatment was 2035 (the yield of the two nitrogen application modes increased by 14.56% and 8.06%, respectively compared with that before adjustment).
(5) Reasonable change of sowing date can improve the final yield of rice to a certain extent. In 2021–2035, the best yield of double-harvest rice can be obtained when the sowing date of early rice is about 15 days earlier and the sowing date of late rice is about 10 days earlier. From 2035 to 2050, the sowing date of double-harvest will be

advanced by about 10 days, and the total yield of double-harvest rice will be higher. In 2050–2070, the total yield of double-harvest rice may reach the best when the sowing date is delayed by 10–15 days.

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