Article

Climate Warming and Crop Management: A Comprehensive Analysis of Changes on Distribution of Suitable Areas for Double Rice

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Abstract: Understanding the effect of climate warming and technological progress on crop production systems is crucial for developing climate adaptation strategies. This study presents a methodological framework with which to assess the suitability of the double rice cropping system in Southern China and the effects of crop management and climate warming on its distribution. The results indicate that the isolated effects of climate warming have led to the northward and westward expansions of double rice northern limits over the past six decades and an increase in suitable areas by 4.76 Mha. Under the isolated effect of crop management, the northern limits of the medium- and late-maturity double rice changed significantly due to the increased accumulated temperature required caused by varietal replacement and planting date change, which moved an average of 123 and 134 km southward, respectively. A combined scenario analysis indicated that crop management could offset the effects of climate warming and push the northern limits southward, reducing the overall suitable area by 1.31 Mha. Varietal replacement and other crop management methods should also be appropriately considered in addition to climate warming to develop locally adapted agricultural management strategies.

Keywords: varietal replacement; double rice; suitable area; climate change; thermal indicator; Southern China

1. Introduction

Despite the steady growth in global food production, the risk of food insecurity has increased due to the pressure of a growing population, shrinking arable land, and climate warming [1,2]. In order to meet an increasing demand for food with limited arable land, people are constantly producing more food through breeding crop varieties, innovative cultivation techniques, and increasing cropping intensity [3–5]. Southern China is the most critical multi-cropping region in China and plays a vital role in ensuring national food security. However, in recent decades, the area of double rice has decreased significantly due to the decline in the economic benefits of rice, changes in cropping systems, and the impact of climate warming [1]. Reforming rice distribution to match climatic resources is of great significance to increase food production in Southern China.

Agriculture is one of the most vulnerable fields to climate change [6]. Climate change, characterized by warming temperature, has produced a series of significant impacts on agricultural resource utilization, farming system distribution, and crop production [7–10]. For example, changes in temperature over the past decades have accelerated the phenological development and advanced maturity of rice [11], thus shortening the rice growth period and decreasing the yield [12,13]. On the other hand, increased crop production is expected when considering the expansion of potential crop growing seasons due to climate warming [14]. Meanwhile, the projected area and total rice production has shown...
an increasing trend for the future [15]. Besides, the change in climate resources caused by climate warming has significantly impacted regional cropping systems and variety distribution [16,17]. For example, previous studies have shown that the northern limits of rice in Northeast China have shifted dramatically to the north by about four latitudes due to climate warming [18]. The northward and westward shift of the crop planting boundary means that the original crop varieties and distribution are unable to adapt to the current climatic conditions [19–21].

In recent decades, breeders have continuously improved rice varieties to increase crop yields and the ability of crop adaptation to climate warming [22]. Varietal replacement is when new varieties gradually replace some old varieties over time. Since the 1950s, rice varieties have been renewed eight times in China, including three times from 1953 to 1977 and five times from 1978 to 2010 [23], and each varietal replacement has greatly improved rice yield potential and stability [24,25]. However, changes in rice growth periods, planting dates, and climatic resource demand brought about by varietal replacement may bring about changes in regional cropping systems and variety distribution, such as the application of long-growing period varieties of double rice in production and the delay of sowing dates [26,27]. Therefore, it is necessary to clarify how crop management has impacted cropping systems distribution in Southern China, which can assist in providing valuable information when optimizing regional rice distribution patterns.

The double rice cropping system is a critical planting system in Southern China and it is also one of the multiple cropping systems with the highest utilization of climate resources. The rice maturity matching pattern in Southern China is rich and diverse, based on the diversity of climate types [28]. For example, the late-maturing double rice cropping system is mainly located in South China because of the abundant thermal resources [29]. In the 1980s, the planting area of double rice accounted for 65% of the total rice planting area in Southern China. However, the planting area of double rice has continued to decline since the 1990s. The proportion dropped to 46% in 2020 [30]. Stabilizing the planting area of double rice in this region is of great significance to ensure national food security. Therefore, studying the impact of climate warming on the planting distribution of double rice cropping systems can provide a reference for the sustainable development of rice in Southern China.

Southern China faces more complex challenges such as climate warming, technological progress, and economic development [1]. The annual and seasonal average temperature in double rice cropping systems generally shows an increasing trend, and the planting dates of rice have also changed significantly, resulting in significant changes in the pattern of agro-climatic resources in Southern China [21,31]. At the same time, the rice in Southern China has undergone several replacements in recent decades, and the constant replacement of new rice varieties has changed the growth period and thermal requirements [22,32]. However, the ways in which climate warming and crop management comprehensively affect the double rice cropping systems in Southern China remains unclear. Previous studies focused more on the effects of climate warming on rice yield. Nevertheless, limited research has been reported on the impact of climate warming and crop management on the northern limits and the potential distribution of double rice cropping systems. The goals of this study were (1) to assess the changes in regional thermal conditions and the thermal demand of double rice cropping systems in the past sixty years; (2) to evaluate the isolated impact of climate warming and crop management on the potential planting distribution of double rice cropping systems with different levels of maturity in Southern China; and (3) to quantify the comprehensive impact of crop management on suitable areas of double rice under climate warming.

2. Materials and Methods

2.1. Study Areas

The area of China addressed in this study consists of 13 central double rice-producing provinces, including Jiangsu, Shanghai, Zhejiang, Anhui, Fujian, Hubei, Hunan, Jiangxi,
Guizhou, Yunnan, Guangxi, Guangdong, Hainan (Figure 1). The cropping systems in this region are double rice-based. The harvested area of double rice accounts for 47.3% of the region’s total and contributes to 41.5% of the regional rice production [30].

Figure 1. Map of the study area, digital elevation model, climate stations, and double rice sites in Southern China. JS: Jiangsu; SH: Shanghai; ZJ: Zhejiang; AH: Anhui; FJ: Fujian; HB: Hubei; HN: Hunan; JX: Jiangxi; GZ: Guizhou; YN: Yunnan; GX: Guangxi; GD: Guangdong; HN: Hainan.

2.2. Data Set

Climate data: The daily climate data were obtained from the climate data-sharing service system of the China Meteorological Administration (http://data.cma.cn (accessed on 3 September 2021)) during 1961–2020. There are 201 meteorological stations in the double-rice cropping system area, including a complete record of daily mean temperatures, maximum temperatures, minimum temperatures, sunshine hours, and precipitation.

Terrain elevation and land use data: The digital elevation model and land use data with a mapping scale of 1:1,000,000 were obtained from the Resource Environmental Science and Data Center (https://www.resdc.cn/Default.aspx (accessed on 10 October 2021)). Considering the topographic effects on climatic data and the diverse topography in Southern China, the meteorological data were interpolated using the elevation data with ANUSPLIN 4.4 (https://fennerschool.anu.edu.au/research/products/anusplin (accessed on 10 October 2021)).

The land use data were used to quantify the effect of crop management and climate warming on the suitable area of different double rice cropping systems. It contains 25 land-cover classes. One is paddy land, defined as cropland with enough water supply and irrigation facilities for planting paddy rice [33]. As this study focuses on double rice production and is mainly concerned with lowland rice in China [34], paddy land can reflect the double rice cropping systems distribution in Southern China (Supplemental Figure S2).

Crop phenological data: Rice phenology data from 1992 to 2013 were obtained from the agro-meteorological experimental stations of the Chinese Meteorological Administration. Overall, a total of 71 agro-meteorological experimental stations in the study area were used, which provide the sowing, transplanting, heading, and maturity date of early and late rice, respectively (Figure 1).

2.3. Methodological Framework

The distribution of the double rice cropping system is closely related to the regional environment and varieties. Therefore, a methodological framework was designed in this article to assess the impact of crop management and climate warming on the distribution of double rice cropping systems in Southern China. A schematic representation of the
methodological framework that we developed is shown in Figure 2. Instructions for the different sections are provided below.

![Figure 2. Schematic representation of the conceptual framework for double rice suitability assessment. ATPGP: accumulated temperature during potential growth period; PGP: potential growth period; SHD: safe heading days; A: the threshold of ATPGP; B: the threshold of PGP; C: the threshold of SHD; DR: double rice; EDR: Early-maturity double rice; MDR: Medium-maturity double rice; LDR: Late-maturity double rice.]

2.3.1. Indicator Selection for Performing the Assessment

As rice is a thermophilic crop, previous literature has empirically suggested that its thermal requirements are the key factors restricting the distribution of rice cropping systems [11, 35, 36]. Three thermal indicators, the accumulated temperature during the potential growth period (ATPGP), the potential growth period (PGP), and the safe heading days (SHD), were used to determine the northern limits of suitable areas for double rice cropping systems. ATPGP refers to the accumulated temperature from transplanting to maturity of the entire rice system, which is the crucial indicator of thermal resources for evaluating rice distribution in China [9, 29, 37]. Meanwhile, PGP is defined as the number of days from rice transplanting to maturity, which is also a critical indicator for crop production, variety selection, and agriculture management and has been widely used in rice climate regionalization in several regions [28, 38, 39]. A lower grain yield caused by low temperature remains a problem in rice production [40]. When the temperature is lower than 15 °C, the probability of rice seedling rot increases significantly and leads to a delayed growth period [41, 42]. Moreover, 15 °C is also the low-temperature threshold at the maturity stage that affects seed filling, which leads to a low seed set and yield loss [43]. Thus, the temperature threshold for the potential growth period of rice in this study was 15 °C. Considering the effect of random fluctuations in daily average temperature, this study used a 5-day moving average method to determine the start date and end date to
avoid unexpected changes in the daily average temperature [44]. Their calculation formulas were as follows:

\[
\text{ATPGP} = \sum_{i=D_t}^{D_m} T_i \geq 15 \, ^\circ\text{C} \quad (1)
\]

\[
\text{PGP} = \sum_{i=D_t}^{D_m} D_i = \begin{cases} 
0 & \text{if } T_i \leq 15 \, ^\circ\text{C} \\
D_i & \text{if } T_i \geq 15 \, ^\circ\text{C}
\end{cases} \quad (2)
\]

where \( T_i \) is the daily average temperature (°C); \( D_t \) is the safe transplanting date of early rice corresponded to the first occurrence of the average daily temperature greater than 15 °C with an 80% probability; \( D_m \) is the safe maturity date of late rice corresponding to the last event of the average daily temperature greater than 15 °C with an 80% probability. \( D_i \) is an individual time step (day).

In the double-rice cropping region in Southern China, the cold-current outbreak at the heading stage of late rice from mid-September to early October often causes increased spikelet sterility and reduces the grain filling rate [45,46]. Thus, SHD was used in this study as an auxiliary indicator, which refers to the number of days from the transplanting date to the heading date of rice [47]. Previous studies have shown that a temperature higher than 22 °C can make rice head safely and increase its yield [47,48]. Therefore, the temperature threshold at the heading stage of rice in this paper was 22 °C. The calculation formula is as follows:

\[
\text{SHD} = D_h - D_t \quad (3)
\]

where \( D_h \) is the last occurrence of the average daily temperature greater than the low-temperature threshold at the heading stage (22 °C) with an 80% probability.

### 2.3.2. Classification of Suitable Area

The double rice cropping systems were divided into three maturity levels (early-maturing, medium-maturing, and late-maturing) due to the vast territory and diversity of double rice varieties in Southern China. Firstly, we calculated the accumulated temperature of above 10 °C of the actual growth period (transplanting to maturity) and busy farming seasons (the harvest of early rice to the transplanting of late rice), actual growth period, and heading days (transplanting to heading) of early and late rice in different years. Secondly, we averaged the data of the same agro-meteorological experimental stations in the 1980s and 2010s, respectively, and divided the maturity of rice varieties according to their growth period based on the work of Tu [47], Zhang et al. [49], and Qin et al. [39]. Finally, by summing up the above data of early and late rice at the same site (Supplemental Table S1), the classification of suitable areas for double rice cropping systems at different maturities in Southern China under crop management in the 1980s and 2010s was obtained in Table 1 (See the supplementary material for more details).

### Table 1. Indicators system for double rice cropping systems in Southern China under crop management in the 1980s and 2010s.

<table>
<thead>
<tr>
<th>Double Rice Cropping Systems</th>
<th>The Accumulated Temperature during Potential Growth Period</th>
<th>Potential Growth Period</th>
<th>Safe Heading Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C Day</td>
<td>Days</td>
<td>Days</td>
</tr>
<tr>
<td>1980s</td>
<td>2010s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EDR *</td>
<td>4000–4500</td>
<td>4300–4700</td>
<td>190–210</td>
</tr>
<tr>
<td>MDR</td>
<td>4500–5000</td>
<td>4700–5300</td>
<td>210–250</td>
</tr>
<tr>
<td>LDR</td>
<td>&gt;5000</td>
<td>&gt;5300</td>
<td>&gt;250</td>
</tr>
</tbody>
</table>

* EDR: Early-maturity double rice; MDR: Medium-maturity double rice; LDR: Late-maturity double rice.

### 2.3.3. Result Visualization

Thermal conditions, including ATPGP, PGP, and SHD would change due to climate warming, so the period from 1961 to 2020 was divided into two periods, i.e., 1961–1990
and 1991–2020 in this study. Based on the daily climate data of the meteorological station data set, the potential thermal conditions of each meteorological station in two periods were calculated with R version 4.0.3 (https://cran.r-project.org/src/base/R-4/ (accessed on 30 October 2020)). Then, the previous calculation results were interpolated to the study area through ANUSPLIN 4.4. Finally, the potential thermal conditions of the study area were divided based on the classification standard in Section 2.3.2, and the results were visualized by ArcGIS 10.2 (https://developers.arcgis.com/ (accessed on 30 October 2020)).

Moreover, the regression coefficient of linear regression was used to estimate the trend of the thermal condition over the past sixty years [50]. The slope was calculated using the following formula:

\[
\text{Slope} = \frac{n \sum a_i \cdot b_i - \sum a_i \sum b_i}{n \sum a_i^2 - (\sum a_i)^2}
\]

where \(n\) is the number of years, \(a_i\) is the \(i\)th year, and \(b_i\) is the corresponding indicator in the \(i\)th year. The trend analysis was examined using Student’s \(t\)-test at 0.05 confidence levels, and all the calculations above were carried out in R version 4.0.3.

2.4. Statistical Analysis

Statistical analyses of the data were performed using Student’s \(t\)-test to identify differences in accumulated temperature during the rice growing period. The software SPSS 25.0 (https://www.ibm.com/products/spss-statistics (accessed on 30 October 2020)) was used to analyze the statistical significance level set to 0.05 or 0.01. The figures were constructed with ArcGIS 10.2 and Origin 2021 software (https://www.originlab.com/ (accessed on 10 October 2021)).

3. Results

3.1. Effects of Crop Management and Climate Warming on the Indicators of Double Rice Cropping Systems

We calculated the changes in thermal conditions in Southern China under climate warming over the past six decades (Figure 3A–F, Supplemental Figures S4–S10). In the past six decades, the thermal conditions of double rice cropping systems in Southern China were high in the southeast and low in the northwest (Figure 3A–C). There was an increasing trend of ATPGP; 77.1% of the stations showed a significant increase \((p < 0.05)\), and the trend represented an increase of 78.65 °C day/decade (Figure 3D). The PGP also increased from 1961 to 2020; 97.0% of the sites increased (significantly at 115 stations) by an average of 2.67 days/decade (Figure 3B). The increases were significantly higher in the middle and lower reaches of the Yangtze River (provinces of Jiangsu, Anhui, Zhejiang, Jiangxi, Hubei, and Hunan) than in other regions, mainly due to the significantly advanced safe transplanting date in this region \((p < 0.05\), Figure 3E, Supplemental Figure S3). An increase in SHD occurred for 194 stations by an average of 2.52 days/decade. A total of 98 sites showed a significant lengthening trend \((p < 0.05)\) and were mainly concentrated in the middle and lower reaches of the Yangtze River (Figure 3C,F).

3.2. Effects of Crop Management and Climate Warming on the Northern Limits of Double Rice Cropping Systems

The combined and isolated effects of climate warming and crop management on the borders of the double rice cropping system are shown in Figure 4. Climate warming shifted the northern limits of each double rice cropping system’s suitable areas northward and westward when the crop management did not change (Figure 4A). Compared with the northern limits during 1961–1990, the northern limits of early-maturity double rice (EDR) moved approximately 74 km northward on average; the most significant shift was about 110 km northward in Jiangsu and Anhui during 1991–2020. The northern limits of medium-maturity double rice (MDR) moved approximately 61 km westward in the middle and lower reaches of the Yangtze River. The northern limits of late-maturity double rice (LDR) changed slightly from 1991 to 2020 compared with 1961–1990.
Opposite to cases with climate warming only, crop management shifted the northern limits of the suitable areas of double rice cropping systems southward and eastward during 1991–2020 (Figure 4B). For EDR, the northern limits shifted approximately 94 km southward on average, of which the maximum shift was about 128 km in Hunan province. The northern limits of MDR and LDR moved to the south by an average of 123 km and 134 km, respectively.

Crop management offset the effects of climate warming on the northern limits of the suitable areas of double rice cropping systems under the integrated impacts of climate warming and crop management (Figure 4C). For EDR, crop management offset the effects of climate warming on the northern limits, resulting in the movement of the northern limits by less than 30 km in most areas. The areas where the northern limits of MDR moved considerably were mainly distributed in Fujian, Jiangxi, and Hunan provinces, with an average southward shift of 62 km. Additionally, the northern limits of LDR moved approximately 97 km southward.

3.3. Effects of Crop Management and Climate Warming on the Spatial-Temporal Changes of Suitable Areas for Double Rice Cropping Systems

We obtained the spatial-temporal distribution of suitable areas for different double rice cropping systems using the overlay of paddy land (Figure 5A–D). In the past sixty years, the increase in thermal resources caused by climate warming allowed for double rice to be planted in some single-rice areas, resulting in an increase of 4.76 Mha in the area suitable for double rice, accounting for 16.2% of the study area. The suitable areas of EDR increased the most, with an increase of 3.74 Mha, accounting for 12.8% of the study region. Moreover, the suitable areas of the MDR and LDR increased by 0.65 and 0.37 Mha, accounting for 2.2 and 1.3% of the study area, respectively.

Figure 3. Thermal conditions of double rice in Southern China from 1961 to 2020. (A,D): Accumulated temperature during potential growth period; (B,E): Potential growth period; (C,F): Safe heading days; (A–C): Average value; (D–F): Linear time trend and statistical significance.
Figure 4. The integrated and isolated effects of climate warming and crop management on the northern limits of double rice cropping systems. (A): The isolated effects of climate warming on the boundaries; (B): The isolated effects of crop management on the boundaries; (C): The integrated effects of climate warming and crop management on the boundaries.

Under the isolated impact of crop management, the suitable areas for double rice in Southern China decreased by 4.22 Mha (14.4% of the study area) as the northern limits of double rice systems moved southward and eastward. The suitable areas of LDR decreased the most, with a decrease of 1.64 Mha, accounting for 5.6% of the study area. The suitable areas for EDR and LDR decreased by 0.99 and 1.59 Mha, accounting for 3.4 and 5.4% of the study area, respectively.

Under the integrated effects, crop management offset the positive impact of climate warming, which shifted the northern limits southward, reducing the suitable areas for the double rice system by 1.31 Mha (4.5% of the study region). The suitable areas of MDR and LDR decreased by 0.62 and 1.25 Mha, respectively. The northern limits of MDR were more responsive to integrated effects than EDR, resulting in the proportion of EDR increasing from 38% to 40% (Figure 5E).
responsive to integrated effects than EDR, resulting in the proportion of EDR increasing from 38% to 40% (Figure 5E).

Figure 5. The effects of climate warming and crop management on the suitable areas of rice cropping systems. (A): The suitable areas of rice cropping systems during 1961–1990 under crop management in the 1980s; (B): The suitable areas of rice cropping systems during 1991–2020 under crop management in the 1980s; (C): The suitable areas of rice cropping systems during 1961–1990 under crop management in the 2010s; (D): The suitable areas of rice cropping systems during 1991–2020 under crop management measures in the 2010s; (E): Changes in the suitable area of rice cropping systems under different scenarios; Scenario 1: Effects of climate warming; Scenario 2: Effects of crop management; Scenario 3: Integrated effects of climate warming and crop management.

4. Discussion
4.1. Assessment Framework for Evaluating the Spatial Distribution of Double Rice Cropping Systems

This study established an assessment framework of planting suitability for double rice cropping systems using historical meteorological data, rice phenology data, and a GIS spatial analysis based on three thermal indicators. We realized a refinement of the classification for the suitability of double rice cropping systems on a large scale. The determination of classification indicators is essential when evaluating the planting suitability of different crops. Most researchers select thermal instead of rainfall and sunshine indicators when...
considering rice suitability distribution [29,39,47]. Yang et al., (2015) analyzed the northern boundary of double rice in China based on the indicator of the annual accumulated temperature of above 10 °C [9]. Ye et al., (2015) evaluated the suitability of various rice cropping systems by using the growing season utilization rate [28]. Three major thermal indicators that affect rice growth and yield were selected in this paper when studying the suitable areas for double rice cropping systems. At the same time, other climatic factors such as precipitation and radiation were not included. The effect of precipitation on rice distribution is not the main limiting factor, primarily because irrigated rice is widespread and paddy land has good irrigation conditions in Southern China [28,51]. Although radiation can affect crop yield by affecting photosynthesis and growth, rice is not sensitive to sunshine and is widely distributed worldwide [29,52]. Therefore, radiation resources are not the main limiting factor for rice distribution. Besides, since transplanted rice is the primary planting method in China [53] and the factory raised seedlings have gradually replaced field seedlings [54], the thermal requirement of rice was generally calculated from transplanting in this study. In reality, if comprehensive factors such as economic profits, production conditions, and agricultural policies are considered in the evaluation indicators, the results of suitable areas for double rice will be more reasonable. However, due to its complexity and technical feasibility, this research is worth exploring in future work.

4.2. Effect of Climate Warming on Double Rice Cropping Systems

Previous studies have shown that climate warming shortened the rice growth duration length in China. The negative effect of warming on the vegetative period was more marked than the reproductive period in early rice, while late rice is the opposite [21]. The shortening of the rice growth period will reduce the accumulation of rice biomass, resulting in a decrease in rice yield [11,55]. As a response, in actual production, early rice is often planted in spring, and the reproductive phase of late rice is concentrated in autumn in order to extend the crop growth period as much as possible to increase yield. However, this maintained rice yield but raised the possibility of exposure to cold stress in early rice during transplanting and later rice in the heading-flowering stages [36]. Climate warming has significantly increased the thermal conditions in most regions of Southern China (Figure 4), and the safe transplanting date in the northern part of the study area has been significantly advanced (Supplemental Figures S4 and S8), which will result in the northwards expansion of early rice without suffering cold events. Meanwhile, the delay of the safe heading and maturity date (Supplemental Figures S3, S8 and S9) also ensured sufficient thermal conditions in the reproductive stage of late rice. All of these factors provide the possibility for long-growing rice varieties selection.

Over the past few decades, climatic warming has expanded the potential growing seasons of crops and has likely resulted in a northward shift of different cropping systems [9,19], which consists of the complex topography and diverse climate types in the study area, which were the reasons for the noticeable spatial differences in the results affected by climate warming [55]. We found that the northern limits of EDR had a relatively sizable moving distance in the northeastern part of the study area due to the significant increase in thermal conditions in this region (Figure 5A), which was comparable to the findings of Duan and Zhou [13]. Meanwhile, this area is suitable for large-scale mechanized farming due to the flat terrain and presents a future potential production area for double rice. Besides, our results showed that the northern limits of LDR were less responsive to climate warming. This is because the northern limits of LDR were located at the edge of mountain and plain areas with an insignificant increase in temperature, which causes the change in the limit to slow down due to differences in elevation [27].

4.3. Effect of Crop Management on Double Rice Cropping Systems

Over the past few decades, the adjustment of rice cropping systems, such as varietal replacement and planting date changes, has accelerated in China [22,56,57]. To improve grain yield, the growth period of some rice varieties tends to increase, which can be
attributed to the common selection of farmers and breeding experts [58–60]. The variation trend of the rice growth period was not consistent due to the difference in rice types and regions. For the double rice, compared with the 1980s, the days from transplanting to the heading of early rice in the 2010s showed an increasing trend; cultivar shifts prolonged the growth period from transplanting to maturity in early rice, but no significant changes were observed for late rice [31]. The cultivars with a prolonged growth period increase the length of time devoted to yield accumulation, resulting in higher yields [61,62]. However, an extension of the growth period caused by the varietal replacement also increased the thermal demand of growth stages for double rice. At the same time, we found that the transplanting date of late rice in the 2010s was delayed compared with the 1980s (Supplemental Figure S1), which means that the busy farming seasons between the harvest of early rice and the transplanting of late rice were also prolonged, which led to the increase of the annual accumulated temperature demand of the double rice cropping system [21,31]. It is undeniable that the change in crop management not only improves the crops yield but also provides diversified choices for production and contributes to the functionality and stability of the food production system [63,64]. However, the resulting reduction in suitable areas means that the impact of crop management on regional food security needs to be comprehensively considered. However, the consequent decrease in the suitable areas requires a careful consideration of the effects of crop management on regional food security.

4.4. Combined Effects of Climate Warming and Crop Management

Climate has led to more suitable areas for rice growing in Southern China [65], but changes in crop management such as varietal replacement and shifts in planting dates have increased the demand for thermal resources [66,67]. This study quantified the impact of crop management and climate warming on cropping systems by analyzing changes in the distribution of suitable areas. The results showed that the suitable areas for double rice cropping systems in Southern China were reduced under the combined effects of climate warming and crop management; that is, changes in crop management offset the impact of climate warming. This study investigated the effect of crop management on the potential distribution of double rice in Southern China from the perspective of technological progress, which will be helpful in understanding the spatial-temporal changes of double rice in production and provide valuable information for guiding rice distribution patterns in Southern China.

Moreover, climate warming has increased thermal resources, which is thought to shift the planting boundaries northward and increase the number of potentially suitable areas for double rice. However, the planting distribution may change in a different way in actual production. We compared the calculated result with the actual distribution of double rice in Southern China (Supplemental Figure S2). The results showed that the actual distribution of double rice was mainly concentrated in the south of the limit line. However, there is a specific difference between the calculated potential double rice distribution in Yunnan, Guizhou, and Jiangsu provinces. One of the reasons is that the increase in thermal demand caused by varietal replacement and planting date adjustment has made the northern boundary move southward, reducing the suitable areas for double rice. Besides, rapid industrialization and urbanization have led to a labor shortage and increased labor costs, which has reduced the net income of farmers and decreased farmers’ enthusiasm for planting double rice in return [1]. Therefore, it is necessary to rationally treat the impact of climate warming on rice distribution in Southern China. The expected increase in rice area due to climate warming has not yet been observed.

5. Conclusions

Our study assessed the isolated and combined effects of climate warming and crop management on the northern limits and suitable areas of double rice cropping systems in Southern China. Our results indicated that climate warming expanded the northern limits of double rice cropping systems northward and westward, thus increasing the number of
suitable areas. However, when considering crop management, the result was the opposite. Variety replacement led to changes in the accumulated temperature required and offset the effect of climate warming. The suitable areas for LDR decreased significantly by 1.25 Mha. Therefore, appropriate measures should be considered in the future to cope with the reduction in suitable areas caused by variety replacement to ensure the stable production of double rice. This study provides a reference for comprehensive assessments of climate warming and crop management impacts on crop production systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12050993/s1, Figure S1: Observed phenological stages (A) and thermal requirements of double rice cropping systems (B) in Southern China from 1981 to 2010; Table S1: Definition of indicators for the distribution of rice cropping systems; Figure S2: The distribution of the land use system in Southern China; Figure S3: The actual distribution of double rice in Southern China in 2020; Figure S4: Thermal conditions of double rice in Southern China from 1961 to 2020; Figure S5: The accumulated temperature during potential growth period in Southern China from 1961 to 2020; Figure S6: Potential growth period of double rice cropping systems in Southern China from 1961 to 2020; Figure S7: Safe heading days of double rice cropping systems in Southern China from 1961 to 2020; Figure S8: Safe transplanting date of double rice in Southern China from 1961 to 2020; Figure S9: Safe full heading date of double rice in Southern China from 1961 to 2020; Figure S10: Safe maturity date of double rice in Southern China from 1961 to 2020.

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