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Agronomic Improvements, Not Climate, Underpin Recent Rice Yield Gains in Changing Environments

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Abstract: Food security depends not only on the extent of climate change but also on the compensatory potentials of agronomic improvements. However, the separate contribution of these agronomic factors to rice yield remains largely unknown. Here we distinguished the impacts and relative contributions on rice yield based on statistical models and machine learning by using an observation database collected from 52 agro-meteorological stations in China from 1981 to 2018. Agronomic improvements are responsible for more than 40% of the observed rice yield change, ranging from 42.9% to 96.5% in different cropping types, and the effect increased with the latitude. Among the management considered, sowing date adjustment contributes most to late and early rice yield. Response of rice yield to nighttime temperature was stronger than that to daytime temperature, and wind speed is the main climatic contributing factor to early rice yield. The effects of wind speed on rice yield should be considered for the adaptation measures. This observation-based evidence may help guide agricultural priorities in mitigating the impact of climate change on rice yield.

Keywords: agronomic improvements; climate change; rice yield; relative contribution

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1. Introduction

Ensuring food security, especially in food production systems, against the negative impacts of climate change is a fundamental priority of the Paris Agreement [1]. Rice is one of the world's most widely grown crops, feeding nearly half the world's population [2]. China is one of the largest rice-growing regions, accounting for 18.5% of the world's total rice planting area and 23% of China's arable land [3]. Changes in rice yield may affect food security as population growth and trade changes have led to rigid growth in food demand. Climate warming beyond the optimum temperature for rice growth has been reported as the main driving factor for yield reduction [4,5]. An assessment of food security by the International Food Policy Research Institute (IFPRI) suggests that climate change could lead to a 10–12% reduction in irrigated rice yields by 2050, excluding CO_2 fertilization [6]. Therefore, quantifying the impacts of climate change and agronomic improvements on rice yields may help to guide adaptation efforts and agricultural priorities.

Climate change directly results in the change of agricultural resources such as heat, water, and light for crop growth. Rice growth is sensitive to climate change, and the extent and direction of responses are complex and vary among regions. Studies based on statistical models or crop models have demonstrated the potential negative impact of climate change on rice yield [7,8]. Increasing temperature accelerates crop development rate and shortens the growing season, leading to earlier anthesis and maturity, which reduces dry matter accumulation, seed weight, and crop yields [9]. Climate warming from 1981 to 2012 shortened rice growth duration by 4.2, 1.8, and 3.9 days for single, early, and late rice [10]. Long-term field experiments showed that a 1 °C increase in nighttime temperature resulted in a 10% reduction in rice yield [11]. Wind speed also affected the growth of rice. Under humid and low wind speed conditions, rice panicle temperature was 4 °C higher than air temperature [12]. Still, the impact of climate change on food production is two-sided. Crop yield potential was increased in high latitudes where the background temperature was low [13]. In northeast China, for example, warming temperature would increase production by extending the growing season and reducing frost damage [14].

Continuous adjustment of agronomic practices sustains productivity under changing climates, such as earlier sowing, harvest date, and genetic improvement (heat-resistant and drought-resistant varieties) [15,16]. Improving crop performance under climate change by changing cultivars and adjusting sowing dates has been widely reported [17,18]. For example, droughts increase the sensitivity of crop yields to temperature [19], while proper irrigation alleviates the negative effects of drought damage [20]. Liu and Dai [21] studied changes in crop varieties and management practices in China over the past 20 years that offset the negative effects of climate change on crop growth and increased crop yields. Masud et al. [22] proposed that varieties with high-temperature resistance and high thermal requirements should be developed to better adapt to climate change and achieve yield increase. However, the adaptation effect also varies with geographical and climatic conditions.

Although previous studies have provided a comprehensive understanding of the impact of climate change on yield, the impact of agronomic improvements remains largely unknown. Therefore, quantifying the yield gain caused by agronomic improvements is needed to adopt appropriate climate change mitigation strategies [23]. Some studies have applied crop models to quantify the impact of climate change and agricultural practices on crops. However, most of the process-based crop models are based on a single point, while the food security issues are mainly manifested at regional or even larger spatial scales. When crop models are transformed from plot scale to regional scale, some assumptions have to be made, increasing the uncertainty of the results [24]. Statistical models have an empirical advantage and are widely used in global change-related research [25,26]. Therefore, based on the observed rice yield data collected from 52 agrometeorological stations in major rice-producing areas in China during 1981–2018, we used improved first-order difference, and random forest models to (1) identify the key climatic factors determining rice yield; (2) distinguish the separate contributions of climate change and agronomic improvements to rice yield changes; (3) quantify the relative effects of cultivar shift, fertilization, and sowing date adjustment on rice yield.

2. Materials and Methods

For this study, 52 agro-meteorological stations with continuous records were selected (Figure 1). Rice yield data from 1981 to 2018 were obtained from local agro-meteorological stations maintained by the China Meteorological Administration and the provincial Meteorological Bureau. Additionally, management data such as cultivar shift, fertilization, and sowing date were also observed and recorded by well-trained agricultural technicians, Chinese agro-meteorological system checked these data. Daily meteorological data from 1981 to 2018 (average temperature (*tem*), maximum temperature (*tmax*), minimum temperature (*tmin*), precipitation (*pre*), sunshine duration (*ssd*), and wind speed (*win*)) were obtained from the China Meteorological Administration China website (http://data.cma.cn/en) (accessed on 28 July 2022).

2.1. Trend Analysis

We combined *Sen* slope estimation with the Mann-Kendall (MK) statistical test to calculate the trends and mutation points of key climatic factors (mean temperature, maximum temperature, minimum temperature, precipitation, sunshine duration, photoperiod, and wind speed) during the growth period. For the MK test, positive values of Z represent upward trends and negative values of Z represent downward trends [27]. $|Z| > 1.96$ and $|Z| > 2.576$ represent significant upward/downward trends at the 0.05 and 0.01 significance levels, respectively [28]. For the MK mutation test, the UF and UB were calculated respectively. If the two curves of UF and UB have intersection points, the intersection point is the mutation point which indicates a significant change around the point. The MK test was calculated using Matlab 2016a (Mathworks Inc., Natick, MA, USA). However, the MK test cannot obtain the slope of the time series. *Sen* slope estimation is robust and widely used in meteorology and hydrology-related studies [29,30]. Therefore, the combination of the MK test and *Sen* slope estimation can effectively estimate the trend of yield and climate factors [31].

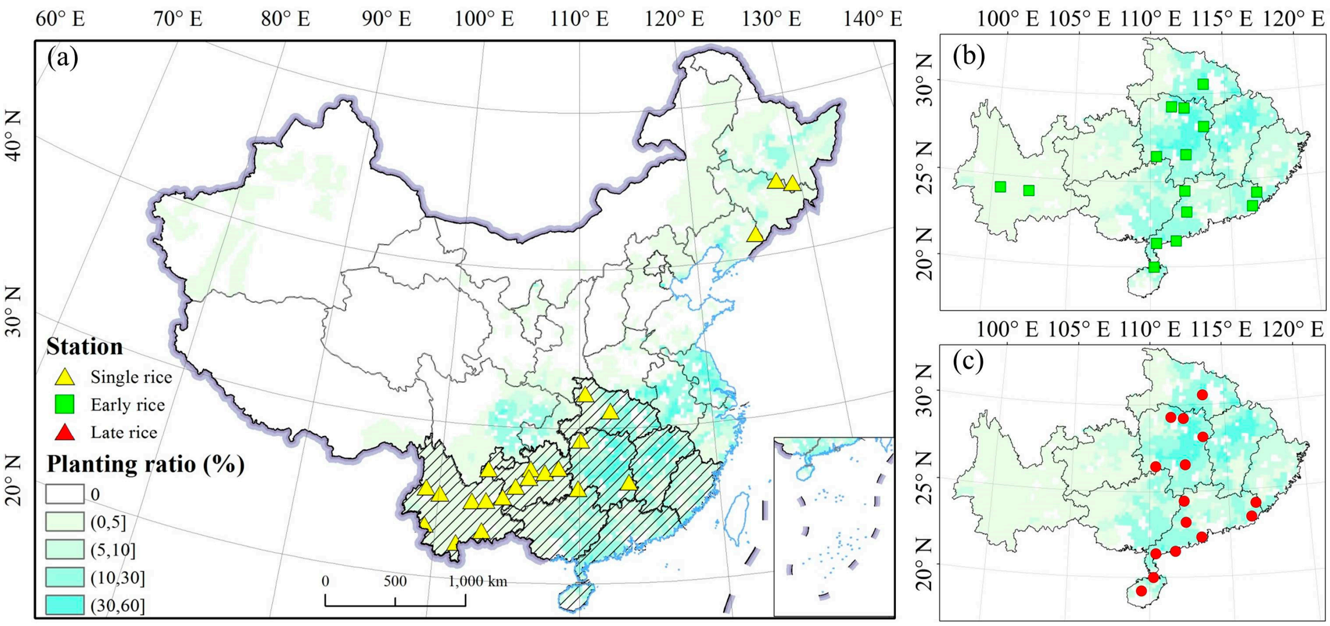

Figure 1. Spatial distribution of rice stations and planting ratio. (**a**–**c**) Early rice, single rice, and late rice, respectively. The shading in (**a**) indicates the planting areas of early and late rice.

2.2. Sensitivity Analysis

Meteorological factors occurred simultaneously, as did the agrotechnical measures. Therefore, to separate the impact of climate change from the observed data, first-order differential was applied to processing the time series of yield and climate data. The first-order difference model has proven able to remove the influence of long-term trends (such as technological progress) on the premise that the technology level is consistent across years [25,32,33].

For selected climatic factors, correlations exist, which might entail uncertainties in estimating the sensitivity of rice yield to changing climatic variables. Therefore, we used ridge regression to exclude the effect of climate covariability on rice yield. Ridge regression can remove the influence of other control factors to effectively derive the effect of a single factor, which can deal with collinearity problems [34]. Because of the interaction of selected climatic factors, it was appropriate to use ridge regression to quantify the response of rice yield to each factor. Regression coefficients were used to quantify the climate sensitivity of rice yield. We standardized yield sensitivity to each climatic factor with the extremal normalization based on previous studies to assess the relative importance of each factor [35].

2.3. Quantify the Effect of the Agronomic Improvement

Based on the sensitivity of yield to climatic factors, the separate impact of climate change on yield is calculated according to the following formula:

$$Y_{cli} = S_{tem} \times T_{tem} + S_{tmax} \times T_{tmax} + S_{tmin} \times T_{tmin} + S_{pre} \times T_{pre} + S_{ssd} \times T_{ssd} + S_{DL} \times T_{DL} + S_{win} \times T_{win} \quad (1)$$

where Y_{cli} represents the changing trend of rice yield affected by main climatic factors (kg ha^{-1} a^{-1}); T_{tem}, T_{tmax}, T_{tmin}, T_{pre}, T_{ssd}, T_{DL}, and T_{win} represent the trends of mean temperature, maximum temperature, minimum temperature, precipitation, sunshine duration, photoperiod, and wind speed during the growth period of rice, respectively, which are calculated by *Sen* slope. S_{tem}, S_{tmax}, S_{tmin}, S_{pre}, S_{ssd}, S_{DL}, and S_{win} represent the sensitivity of mean temperature, maximum temperature, minimum temperature, precipitation, sunshine duration, photoperiod, and wind speed for rice yield. The observed yield trend is the result of a combination of climate change and agronomic improvements. Thus, the individual impact of agronomic improvements on rice yield is calculated indirectly according to the following calculation:

$$Y_{man} = Y_{all} - Y_{cli} \tag{2}$$

where Y_{man} represents the changing trend of rice yield under the influence of agronomic improvements alone. Y_{all} represents the observed trend of rice yield change (kg ha^{-1} a^{-1}).

2.4. Distinguish the Relative Contribution of Climate Change and Agronomic Improvements to Yield

For each site, the contribution of climate change relative to agronomic improvements (RC_{cli}) is shown in Equation (3):

$$RC_{cli} = \frac{Y_{cli}}{|Y_{cli}| + |Y_{man}|} \times 100\% \tag{3}$$

Similarly, the contribution of agronomic improvements (RC_{man}) to rice yield at each site was calculated using this formula. The average relative contribution of climate change ($\overline{RC}_{cli}$) is shown in Equation (4):

$$\overline{RC}_{cli} = \frac{\sum_{i=1}^{n} RC_{cli,i}}{\left|\sum_{i=1}^{n} RC_{cli,i}\right| + \left|\sum_{i=1}^{n} RC_{man,i}\right|} \times 100\% \tag{4}$$

where n represents the number of sites included in the planting type. $\overline{RC}_{cli}$ is the contribution of climate change on rice yield for specific cropping types. $RC_{cli,i}$ and $RC_{man,i}$ denote the relative contribution of climate change and agronomic improvements at the ith site, respectively. Similarly, the average relative contribution of agronomic improvements to different rice cropping types can be calculated according to this formula, expressed as $\overline{RC}_{man}$.

Random forest is an ensemble learning method for classification, regression, and other tasks that operates by constructing a multitude of decision trees at training time and outputting the class that is the mode of the classes (classification) or mean/average prediction (regression) of the individual trees [36]. The random forest method can explain the nonlinear response of yield to management and separate the effects of each variable [37]. Therefore, random forests were used to rank and quantify the importance of each agriculture practice (sowing date adjustment, nitrogen fertilizer, variety replacement) to rice yield. The random forest was calculated using Matlab 2016a (Mathworks Inc., Natick, MA, USA).

3. Results

3.1. Climate Change during the Growing Season and Yield Trend

The changes in climatic factors in the growing seasons and yield trends are shown in Figure 2. In the past 40 years, rice yield showed an increasing trend, and the trend of single/early/late rice yield was 165.41/179.22/200.63 kg ha^{-1} per decade, respectively. The mutation points of the yield changes generally occurred after 2010, accounting for 63.6%, 66.7% and 80.0% of stations of single, early, and late rice (Table 1).

The average temperature in the rice-growing season increased by 0.19 °C per decade, and the magnitude of the minimum temperature increase was larger than that of the maximum temperature. In the growing season of single and late rice, the climate was dry and hot, and the decreasing precipitation trend was 0.74 and 0.41 mm per decade, respectively. The median variation trend of sunshine duration at all stations was −23.61 h per decade. Sunshine duration in the growing season of late rice decreased with the latitude. Wind speeds change the microclimate by affecting evapotranspiration and soil moisture [38]. We found that wind speed decreased during the growing season of single rice but increased in early rice and late rice, with a trend of 0.05 and 0.08 (m s^{-1}) per decade, respectively.

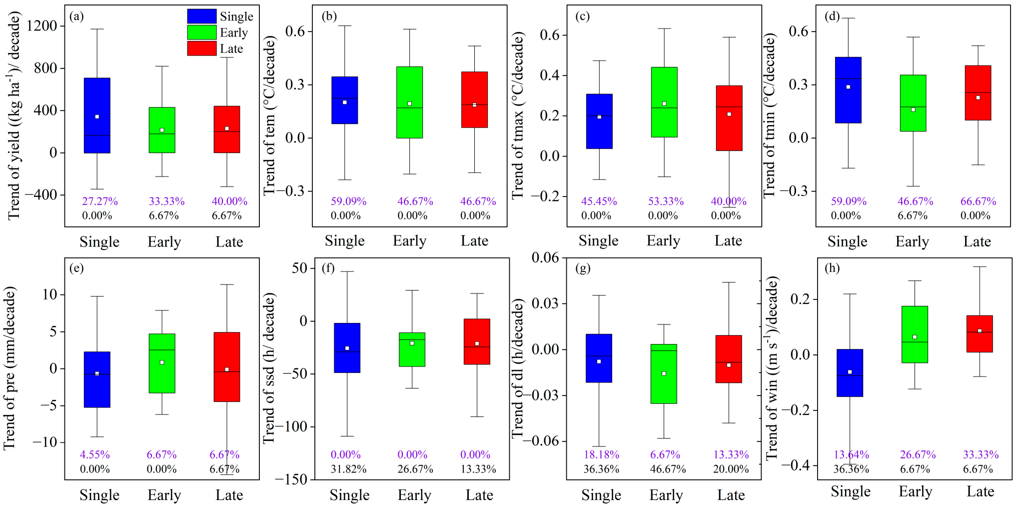

Figure 2. Trends of yield (**a**) and climatic factors (**b**–**h**) in rice-growing season from 1981 to 2018. Purple fonts indicate the percentage of sites that have significantly increased, and black fonts indicate the percentage of sites that have significantly decreased. (**b**–**h**) The trend of mean temperature, maximum temperature, minimum temperature, precipitation, sunshine duration, photoperiod, and wind speed, respectively.

Table 1. Mutation points of rice yield at each station from 1981 to 2018 based on MK test.

Single Sites	Mutation Year	Early Sites	Mutation Year	Late Sites	Mutation Year
Wu Chang	2009	Jing Dong	1990	Xiao Gan	2011
Ning An	2018	Yu Xi	1989	Nan Xian	2010
Xin Bin	2006	Xiao Gan	2010	Chang De	2014
Zhao Tong	2012	Nan Xian	2014	Zhang Sha	2018
Bao Shan	2010	Chang De	2013	Wu Gang	2013
Da Li	2012	Zhang Sha	2012	Heng Yang	2011
Kun Ming	1995	Wu Gang	2014	Lian Xian	2018
Lu Liang	2018	Heng Yang	2015	Mei Xian	2014
Pu An	2015	Lian Xian	2011	Gao Yao	2013
Geng Ma	2017	Mei Xian	2018	Chao Zhou	1984
Jiang Cheng	2018	Gao Yao	2014	Zhong Shan	2018
Meng Zi	2018	Chao Zhou	1987	Hua Zhou	1987
Fang Xian	2018	Hua Zhou	1985	Yang Jiang	2018
Zhong Xiang	2016	Yang Jiang	2016	Qiong Shan	2018
Sang Zhi	2013	Qiong Shan	2014	Qiong Zhong	2013
Zun Yi	2009				
Yu Qing	2018				
Jiang Kou	2010				
Pu Ding	1982				
Li Ping	2012				
Gui Dong	2018				
Hui Shui	2010				

3.2. *Response of Rice Yield to Climate Change*

The sensitivity of rice yield to climate variables obtained by the ridge regression model is shown in Figure 3. The positive and negative signs indicate the response direction of the yield change. The yield of early rice was more sensitive to climatic factors compared with the single and late rice. The single, early, and late rice yields changed −29.99, 49.98 and −43.44 kg ha^{-1} per degree of temperature increase, respectively. The increase in mean temperature, daytime temperature, and nighttime temperature negatively affected yield. Meanwhile, a rise in temperature in the early growing season was beneficial to increasing yield. Increased precipitation resulted in 91.87 kg ha^{-1} and 21.68 kg ha^{-1} yield reduction in single and late rice, respectively. The increase of sunshine duration by 100 h resulted in 1.57, 1.18 and 0.20 kg ha^{-1} yield reduction of single, early, and late rice, respectively. The wind speed increased by 1m/s, and the yield of single rice and early rice increased by 222.15 and 290.56 kg ha^{-1}, respectively, while that of late rice decreased by 72.51 kg ha^{-1}. The dominant climatic factors of yield change of different types of rice are different. The yield of single rice was mainly controlled by nighttime temperature, wind speed, and sunshine duration. The relative importance of wind speed and photoperiod to early rice yield was 0.79 and 0.64, respectively. The relative importance of sunshine duration, precipitation, mean temperature, and daytime temperature to late rice yield was more than 0.5. In general, the temperature had a dominant effect on rice yield, while the effect of precipitation was relatively weak.

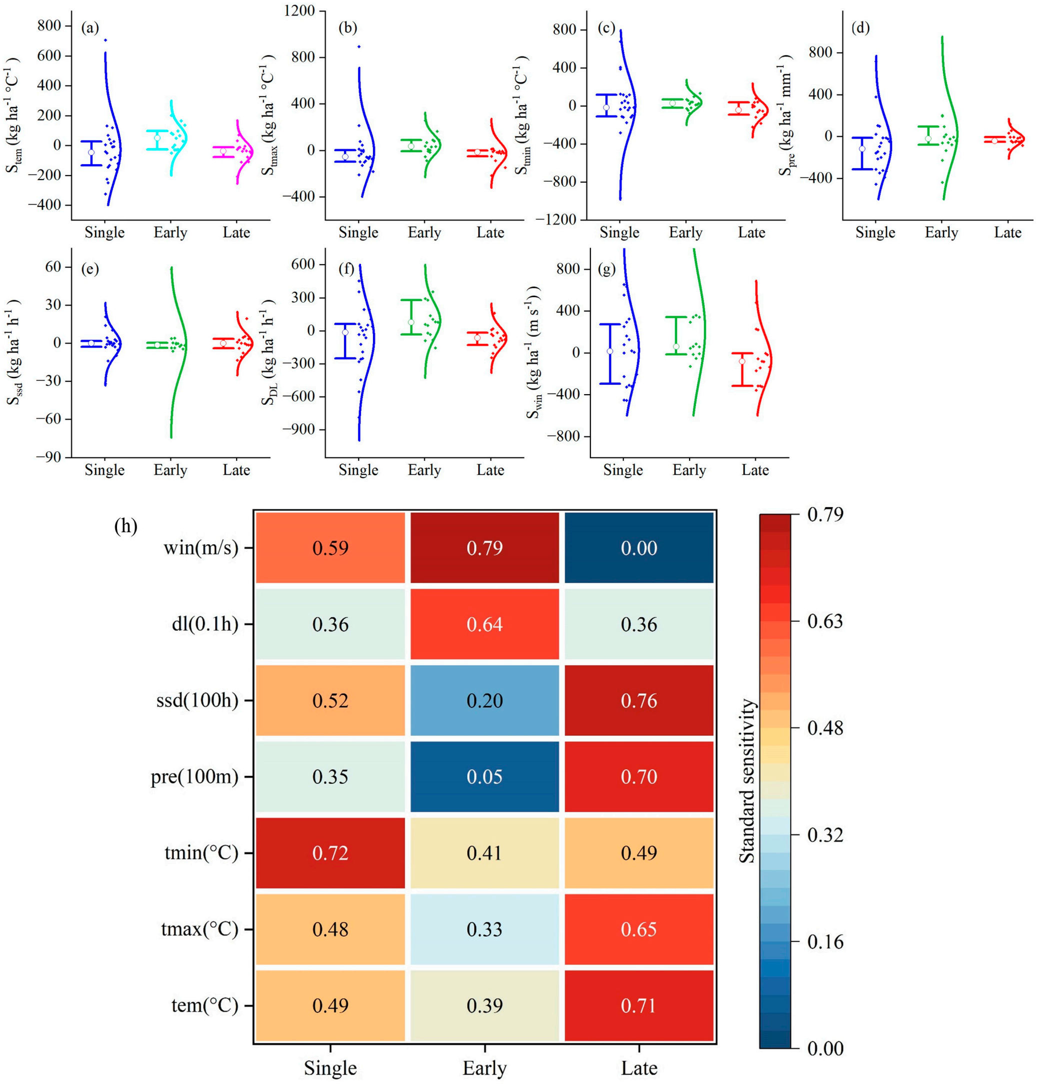

Figure 3. Sensitivity of rice yield to climatic factors (**a**–**g**) and relative importance (**h**). (**a**–**g**) Sensitivity of rice yield to mean temperature, maximum temperature, minimum temperature, precipitation, sunshine duration, photoperiod, and wind speed, respectively.

3.3. Impact of Agronomic Improvements on Rice Yield

The trend of rice yield under the influence of climate change and agronomic improvements is shown in Figure 4. Agronomic improvements mitigate or even reverse the adverse effects of climate change, resulting in yield increases at each site. The average effect of climate change and agronomic improvements on rice yield was 2.85 and 23.39 kg ha^{-1} per year, respectively. In terms of rice types, climate change generally harmed late rice and promoted the yield increase of single and early rice. As for the spatial distribution, the negative climate impact on rice yield was higher in the main grain-producing areas (Heilongjiang and Hunan) than in non-agricultural provinces (Guizhou and Hainan). Agronomic improvements harmed yield at some stations located in low latitude, indicating that adaptation measures are not always effective in a changing environment. Under the isolated impact of climate change, the trends of single, early, and late rice yield were 4.32, 5.40 and −1.18 kg ha^{-1} per year, respectively. The effects of agronomic improvements were 29.93, 16.03 and 24.20 kg ha^{-1} per year. The effects of agronomic improvements on crop yield were spatiotemporal and gradually increased with the latitude.

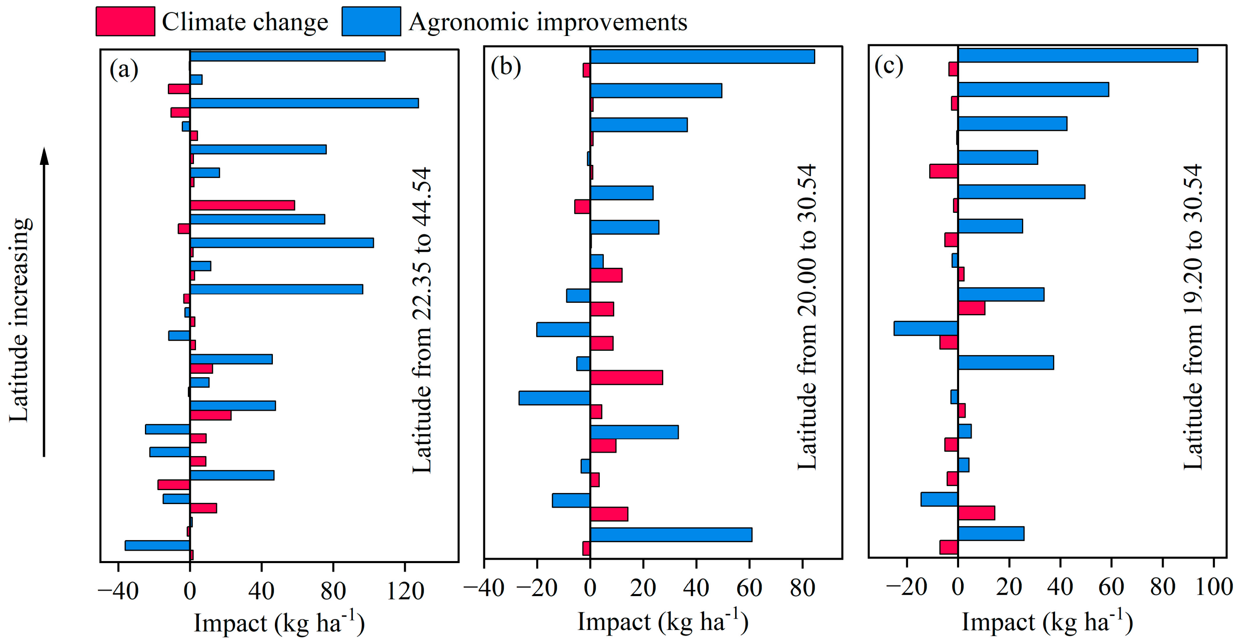

Figure 4. Effects of climate change and agronomic improvements on rice yield at different stations. (**a**–**c**) Single rice, early rice, and late rice, respectively.

3.4. The Relative Contribution of Climate Change and Agronomic Improvements to Yield

The relative contribution of climate change and agronomic improvements to rice yield is shown in Figure 5. The positive and negative contribution indicates the response direction of rice yield. We found that the relative contribution of agronomic improvements to rice yield is much larger than that of climate change and plays a leading role in the yield change. The contribution of agronomic improvements to single/early/late rice yield was 73.0%, 42.9% and 96.5%, respectively. The proportion of stations with a positive relative contribution of single/early/late rice was more than 50.0%. The contribution of climate change to single/early/late rice yield was 27.0%, 57.1%, and −3.5%, respectively. Farmers will take multiple targeted measures to adapt to climate change in the changing climate, such as fertilization, sowing date adjustment, and variety replacement. Crop management records (Table 2) show that rice cultivars shift frequently. Varieties of single/early/late rice have changed more than 20 times during the last 40 years. The results confirm that cultivar shift is an essential adaptation measure, and the number of cultivar shifts is similar to the number of varieties, indicating less use of duplicated varieties. The sowing date of single rice and late rice was delayed by 0.53 and 2.22 days per decade, while the sowing date of early rice was advanced by 0.19 days.

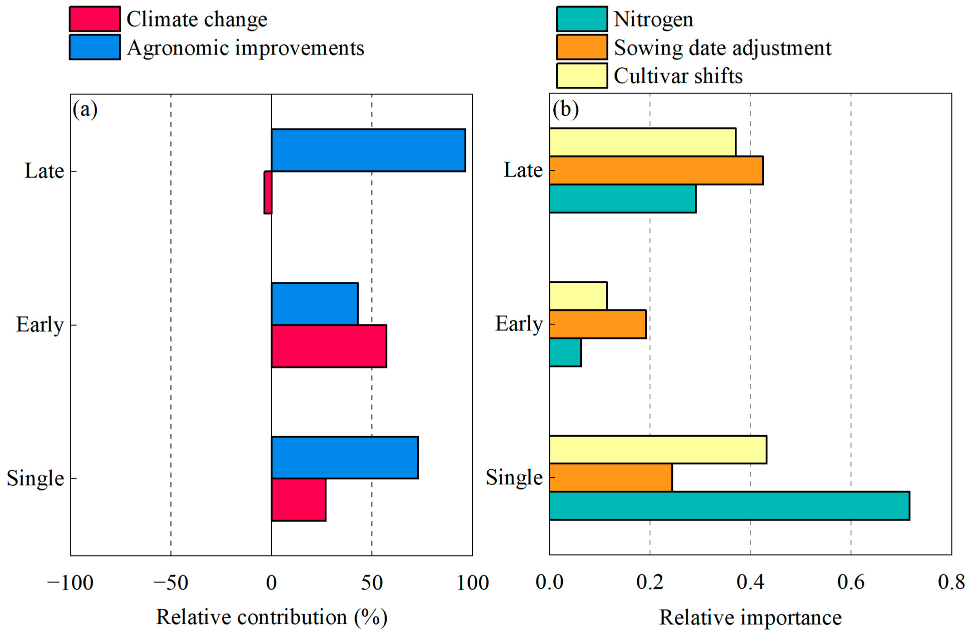

Figure 5. The relative effects of climate change and agronomic improvements on rice yield. (**a**) is the relative contribution of climate change and agronomic improvements. (**b**) is the relative contribution of each measure.

Table 2. Summary of adaptation measures for rice agriculture from 1981 to 2018.

Type	Nitrogen (kg/ha)	Trend of Sowing Date (Days/Decade)	No. of Varieties	No. of Cultivar Shifts
Single rice	148.20	0.53	19	23
Early rice	179.00	−0.19	19	28
Late rice	151.46	2.22	17	29

4. Discussion

Rice yield was sustained at a certain level in China before 2010, and the yield inflection point appeared in 2010. We separated the relative contributions of climate change and agronomic improvements. Agronomic improvements were sufficient to alleviate the negative effect of changing climate on yield potential. Without adaptation to climate change, the potential yields of rice in China by 2050 are projected to be 4.3–12.4% lower than those in 1961–1990, respectively, which is more sensitive than the global average [39,40].

Strong negative effects of climate change have been reported as affecting important processes such as biomass growth rate, growing season length, and grain formation [41–44]. Among the climatic factors considered, warmer average temperatures contributed to the yield loss of single and late rice, partially due to the increasing temperature, shortened growth periods, and hampered rice yield [45]. Compared with average temperature, the negative effect of warmer nighttime temperature on single rice yield was relatively larger. Some scholars have reduced the uncertainty by combining field experiments with crop models, while also showing the negative impacts of warmer nighttime temperatures on yield [11,46]. Yield losses reached 10–20% with nighttime temperatures rising above 28 °C [47]. Rice pollen viability was reduced by warmer night temperatures [48]. Furthermore, warmer night temperatures resulted in enhanced nocturnal respiration after anthesis and reduced soil water availability, thus affecting the duration of the reproductive growth stage [47]. Therefore, the impact of nighttime temperature on rice yield deserves attention.

On the contrary, mean temperature has a positive effect on early rice yield, which is contrary to single and late rice. Early rice was sown in the cool season of the year when the air and soil temperatures are usually lower than the optimal temperature for rice growth, which may contribute to the divergent effect of warmer temperatures. Previous studies have shown that climate warming can increase the effective accumulated temperature of the rice-growing season in northeast China and reduce the effects of frost damage [49]. There is observational evidence that warmer producing areas are more likely to suffer production risk compared with cooler regions [50].

Rice yields have been limited by insufficient photothermal resources, especially in southern China in the past years [51]. Besides temperature, the impact of sunshine duration and photoperiod were also detected in this study. Contrary to the previous studies, which gave much greater weight to temperature, we found that wind speed and photoperiod had comparable contributions to that of temperature. Wind speed changes the microclimate of crop growth by affecting evapotranspiration and soil moisture. For example, reduced wind speed can reduce crop leaf surface dryness and reduce plant leaf shedding [52]. We found that the effect of photoperiod on rice yield is non-negligible. Some studies have reported that the variation in the length of the vegetative growth period may be the result of the interaction of temperature and photoperiod [51,53]. Photoperiod affects photosynthetic efficiency and other biological characteristics of crops. Previous studies indicated that chilling and photoperiod affect vegetation growth [54]. Similarly, photoperiod alters phenological responses to climatic factors by influencing the accumulated temperature requirements of crops [55]; this study confirmed this conclusion. Rice is a short-day crop, and its latitude adaptability is mainly related to photoperiod [53]. We found that precipitation has a negative effect on rice yield, which may be due to the different water requirements at different growth stages, and flooding is not conducive to rice growth, especially before the three leaves stages.

Our results confirm that agronomic improvements were sufficient to maintain rice yield at steady levels in changing climates. The number of cultivars is close to the number of cultivar shifts from 1981 to 2018, suggesting that breeding cycle advancement facilitates climate change adaptation by increasing genetic yield potential [18]. Ahmad et al. [45] compared observed with simulated yield changes and concluded that rice varieties with higher thermal requirements stabilized the duration of critical growth stages. We found that the application of fertilizer was the main management driver affecting the single rice yield. Indeed, fertilization management has significantly boosted crop production in China [56]. Fertilization plays an important role in yield when soil nutrient supply is low. However, skyrocketing fertilizers in China raise non-negligible environmental concerns, such as soil acidification and water pollution [57–59]. Planting date adjustment determines the yield-limiting conditions related to the climate. The regional observation-based evidence has highlighted the advantage of a suitable sowing date [60]. By changing the planting date (moving the growing season to the cooler season) and slowing the development rate of crops, more time for dry matter accumulation is beneficial to yield increase [61]. Previous studies have highlighted the importance of timely sowing to avoid yield loss caused by heat stress [62,63]. There is also a view that one or two weeks of sowing changes will have little effect on crop growth under suitable soil moisture conditions [64]. We found that planting dates for single and late rice have been delayed by about 2–8 days over the past decades. The adjustment of the sowing date is the key management measure affecting early and late rice yield, even moreso than the contribution of variety replacement. Recently, a study also revealed that sowing date has an important impact on yield, surpassing all other crop management, soil, and variety factors [65], which strongly supports our results. Therefore, improving climate resilience and productivity by time management should be highlighted in future adaptation measures.

Based on statistical models and machine learning, this study isolated and quantified the impacts and separated contributions of climatic factors and agronomic improvements on rice yield. Although the statistical method can eliminate the influence of slow trends and has an empirical advantage, there are still large uncertainties due to the inherent errors in the historical data set input. At the same time, although sunshine duration, wind speed, photoperiod, and other previously neglected climatic factors were considered in this paper, CO_2 concentration, extreme climate, and other factors also had important effects on rice yield [66,67]. The effects of these factors on rice yield need to be further assessed in future studies. In addition, although statistical models reflect the relationship between climatic factors and rice yield, there is still a lack of mechanical explanation. Comprehensive analysis combining statistical and process mechanism models can be advocated in future studies.

5. Conclusions

From 1981 to 2018, the average temperature, daytime temperature, and nighttime temperature in the rice-growing season increased, while sunshine duration and photoperiod decreased, precipitation decreased in the single and late rice-growing seasons, and wind speed increased in the early and late rice-growing seasons. Under the combined influence of climate change and agronomic improvements, 27.3%, 33.3%, and 40.0% of the sites of single/early/late rice showed an increased yield, respectively. The sensitivity analysis showed that the sensitivity of single and late rice yields to daytime and nighttime temperatures were negative, and the effect of nighttime temperature on rice yield was greater. Appropriate warming was beneficial to the early rice yield increase. The increase in wind speed benefited the single and early rice yield and was one of the leading climatic factors for single and early rice yield. Therefore, it is necessary to incorporate the influence of this factor into the process model to reduce the uncertainty of simulation. Contribution results showed that agronomic improvements played a dominant role in yield gain. Among the agricultural practices considered, nitrogen fertilizer had a relatively large effect on single rice, while sowing date adjustment had a relatively large effect on late rice and early rice. Duplicate varieties were rarely used, indicating breeding cycle advancement over the past 40 years. Thus, genetic yield potential is essential to achieving yield increase. Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

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