Agronomy for Sustainable Development (2024) 44:23
https://doi.org/10.1007/s13593-024-00963-7

META-ANALYSIS

Adopting agronomic strategies to enhance the adaptation of global rice production to future climate change: a meta-analysis

Saiya Li[1,2] · Feng Wu[1,2] · Qing Zhou[3] · Yali Zhang[1,2]

Accepted: 28 March 2024 / Published online: 16 April 2024

Abstract
The impact of climate change on rice yield varies among different rice varieties. Designing effective agronomic adaptation strategies is crucial for global rice provision. However, considerable uncertainty remains as to which approaches/strategies should be used in different regions. To this end, we conducted a meta-analysis aimed at quantifying firstly the marginal effects of climate change (i.e., temperature, precipitation, and CO_2) and four adaptation strategies (i.e., changing varieties, adjusting fertilization, adjusting irrigation, and altering planting dates) on rice yield in Indica, Japonica, and Hybrid rice. We further assessed climate risks to rice yield and identified optimum adaptation strategies under three shared socio-economic pathway (SSP) scenarios. The results of the meta-analysis showed that temperature has the greatest negative marginal effect of −3.11% on rice yield, with changing varieties being the most effective strategy (15.93%) to counter this effect, followed by increased irrigation (0.24%). Projected climate scenarios predict a 2.11% global average rice yield decrease in the 2040s under SSP5-8.5. Japonica rice yields are significantly more pessimistic than Indica and Hybrid rice. To offset this, 86.48% of the rice planting area would need to change varieties; increase fertilization and irrigation by 51.22% and 8.54%, respectively; or plant in advance by 13 days. Major rice-producing countries such as India, China, and Brazil will need adaptation strategies with higher urgency and scale than the global average. These findings form a basis for a better understanding of climate resilience in different rice varieties and agronomic strategies. Our analysis suggests that it is possible for future rice yield to meet the needs of rice-growing countries while supporting eco-friendly rice production if the appropriate measures are taken. Overall, this study attempts firstly to design effective agronomic adaptation strategies to enhance rice production resilience against climate change and advance understanding of rice varietal adaptation for improved management.

Keywords Rice yield · Climate change · Agronomic adaptation strategies · Resilience · Meta-analysis

1 Introduction

Rice (*Oryza sativa* L.) is the most important staple food for more than 50% of the world's population (Seck et al. 2012; Saito et al. 2017). Global rice production is predominantly concentrated in Asia, where 11 countries contribute approximately 87% of the world's total rice production (Bandumula 2018). China and India, being giant economies of Asia, play a crucial role, contributing to 50% of both rice production and consumption (Muthayya et al. 2014). Global rice consumption is projected to be nearly 550 million tons by 2030, driven by both population increase and economic growth in developing countries (Durand-Morat and Bairagi 2021). However, climate change seriously threatens rice production levels required to feed the future ever-increasing world population. Compelling evidence from various global studies underscores the significant and predominantly negative impacts of future climate on rice yields (Sridevi and Chellamuthu 2015; Akinbile et al. 2020; Wang et al. 2020). A food security assessment by the International Food Policy Research Institute highlights that, excluding the separate effects of carbon dioxide (CO_2) fertilization, climate change is projected to cause a 10%–12% reduction in global irrigated rice yield by 2050 (Nelson et al. 2010). Such a reduction in rice yield signifies a severe threat to global food security, particularly given the speedy increase in the

✉ Yali Zhang
zhangyali@igsnrr.ac.cn

[1] Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2] University of Chinese Academy of Sciences, Beijing, China

[3] College of Public Administration, Huazhong Agricultural University, Wuhan 430070, China

world's food demand (Alexandratos and Bruinsma 2012; Rogelj et al. 2016). This issue would thwart sustainable development programs for achieving the universal goal of eliminating hunger by 2030.

Therefore, it is critical to assess which regions will be affected most, as well as to develop potential future agronomic adaptation strategies that improve the climate resilience of rice and meet global rice demand. Climate change adaptations refer to actions that mitigate damages or exploit beneficial opportunities related to climate change (Parry et al. 2007; Lobell 2014). How rice production systems can better adapt to a range of future climate change scenarios to improve resilience has become a key concern.

Diversifying varieties, improving potential productivity, and harmonizing crop growth with climatic conditions offer a variety of entry points for adapting crops to projected climate change (Challinor et al. 2007; Howden et al. 2007; Ali and Erenstein 2017; Tesfaye et al. 2019). These entry points have proven track records toward making varieties more resilient to climate variability. Variety diversification plays an important role in the adaptation to a changing environment. Various rice varieties can tolerate the impacts of a fluctuating climate, such as high temperatures, floods, and droughts, to different degrees. Thus, knowing the most appropriate rice varieties under particular conditions can help to address challenges imposed by future climate conditions (Fao 2007; Babel et al. 2011a, b; Yoshida et al. 2015; Chun et al. 2016a, b; Guo et al. 2019a, b). The rich diversity of rice in Kerala, India, as reported by Gopi and Manjula (2018), provides opportunities to adapt to stresses induced by climate change. Likewise, maximizing potential rice productivity through fertilizer and irrigation management can offset climatic shocks (Babel et al. 2011a, b; Liu et al. 2013; Boonwichai et al. 2019a, b; Islam et al. 2020a, b). Shrestha (2014) showed that supplementary irrigation of rice in the winter season can achieve a yield increase of up to 42%, and increasing the fertilizer application rate can enhance the yield from 0.3% to 29.8% under projected future climates in the Quang Nam province (Vietnam). Rajwade et al. (2018a, b) showed that a higher dose of N fertilizer was able to mitigate the negative impact of a temperature increase of up to 3.3 °C over the period of 2012–2014 in subtropical India. Also, literature consensus underscores that synchronizing critical rice phenophases with favorable weather conditions through altering planting dates ensures a promising crop yield (Shelley et al. 2016; Acharjee et al. 2019; Guo et al. 2019a, b; Ding et al. 2020). Jalota and Vashisht (2016) estimated that delaying the planting of rice by 7–15 days in the semi-arid Indian Punjab in the future was a doable adaptation measure to minimize yield reduction in the future. Hussain et al. (2020) showed that adopting a climate-smart cropping pattern by shifting the planting date and adjusting the cropping season could reduce the risk of heat-induced losses.

Various approaches have been employed to evaluate the impacts agronomic adaptation strategies have on rice yields, such as changing varieties (Chun et al. 2016a, b; Koppa and Amarnath 2021), altering planting dates (Ding et al. 2020; Truong An 2020), and adjusting both irrigation and fertilizer application (Arunrat et al. 2020a, b; Liu et al. 2020a, b). One technique is the use of field experiments, which was employed to evaluate rice cultivar adaptation to elevated CO_2 levels and temperature in sub-tropical India (Satapathy et al. 2014a, b). Another technique is to utilize statistical (or empirical) models to condense observed relationships between adaptation and the yield of rice (Hu et al. 2017). A prevalent method in the literature involves the use of process-based crop simulation models and climate change scenarios to investigate the future impact of climate change on crop yields (Boonwichai et al. 2019a, b; Halder et al. 2020a, b; Islam et al. 2020a, b; Truong An 2020). Crop models can be used to characterize the dynamics of plant growth and development and provide a relatively simple and cost-effective method for evaluating the effects of climate change and adaptation. Process-based crop simulation models parameterize the daily dynamics of management, weather, soil, and plant processes and can be used to project future rice yields. Climate change data are commonly generated by general circulation models (GCM) for a variety of emission scenarios.

However, existing literature often has obtained heterogeneous results because of differences in methods, regions, and scenarios; this, in turn, leads to considerable uncertainty. To address this, we conducted a meta-analysis using an updated and comprehensive data set to examine the response of rice yield to climate change and different agronomic adaptation strategies. Meta-analyses that combine and compare results from numerous studies are a useful means for summarizing the range of projected outcomes in the literature and assessing consensus (White et al. 2011). The advantage of this method is that, by analyzing the results from a large number of studies, meta-analysis can be used to identify a significant trend even where many individual studies might have failed to detect such a trend. However, prior meta-analyses mainly focused on the response of rice yields to climate change with or without adaptation strategies. So far, how rice yields respond to different agronomic adaptation strategies remains understudied. Crucially, our study addresses this gap by not only considering the response of rice yields to climate change but also examining the effectiveness of various agronomic adaptation strategies. Furthermore, we go beyond the scope of previous studies by quantifying the significance and magnitude of the impacts these factors exert on the yields of different rice varieties.

The objectives of this study are to quantify the marginal effects of climate change (i.e., temperature, precipitation, and CO_2) and four adaptation strategies (i.e., changing varieties, adjusting fertilization, adjusting irrigation, and altering planting dates) on rice yields in the rice varieties Indica, Japonica, and Hybrid rice. Based on the results, the future climate risk of rice yield is assessed. In this study, the impact of climate change on rice yield is projected from the baseline period (2015–2020) to the medium-term period (the 2020s, 2030s, and 2040s) under three shared socio-economic pathway (SSP) scenarios. Finally, the scale of different agronomic adaptation strategies is quantified to precisely offset the negative climate change shocks to global rice yield, following the question: which adaptation strategies will be required where? The findings of this study highlight the response of rice yield to climate change and provide important insight into the most effective adaptation to improve rice climate-resilience on a global scale in the future, which will help to ensure global food security.

2 Methods

2.1 Data collection

In this study, advanced literature searches were conducted to identify articles published between 1990 and March 2021 related to rice production under climate change and adaptation. Databases such as the Web of Science, Science Direct, Google Scholar, and the Chinese National Knowledge Infrastructure were used. These publication databases were searched using the Boolean string of ("rice production" OR "rice yield") AND ("climate change") AND (adapt*). Screening of the publications followed the PRISMA approach (Liberati et al. 2009) and resulted in the identification of 247 publications (Supplementary Fig. 1). Furthermore, publications were included in the meta-analysis if the following requirements were met: (a) the study involves an analysis of the impact of climate change and adaptation strategies on rice yield; (b) the study contains at least one response variable from the following list: rice yield, rice production, or grain weight; (c) the study involves the effect of at least one climate variable from the following list: temperature change, CO_2 concentration, or precipitation change; (d) the study includes at least one adaptation strategy from the following list: changing varieties, changing sowing dates, adjusting fertilization, or adjusting irrigation. Data were extracted from the text or tables of selected articles. When data were not directly accessible, the data were manually transcribed from tables or digitally retrieved from graphs using WebPlotDigitizer 4.0.0 software.

The global climate model (GCM) ensemble was obtained from CMIP6 archives that provided data for both historical and future periods. Three integrated scenarios were considered (i.e., combining SSP2 with representative concentration pathway (RCP) 4.5, defined by SSP2-4.5; combining SSP3 with RCP7.0, defined by SSP3-7.0; and combining SSP5 with RCP8.5, defined by SSP5-8.5). Five CMIP6 global circulation model datasets (i.e., GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and BCC-CSM2-MR) were used to generate climate data for baseline periods (2015–2019) and three future periods (the 2020s, 2030s, and 2040s). Climate data for the 2020s, 2030s, and 2040s represented the average data over 10 years, i.e., from 2020 to 2029, from 2030 to 2039, and from 2040 to 2049, respectively. The temperatures, precipitation levels, and CO_2 concentrations under CMIP6 climate projection were downscaled (at a $1 \times 1°$ grid size resolution), and bias correction was analyzed (Chaowiwat 2016; Chaowiwat et al. 2019). After the selection of GCMs, mean variability scenarios were computed as average monthly temperature, precipitation, and CO_2 concentration data from all GCMs. Changes in temperature, precipitation, and CO_2 concentration were calculated by comparing baseline data with the data of each of the three future decades. In this process, solar radiation, winds, and relative humidity were assumed to remain unchanged.

2.2 Database description

In total, 2949 data points/observations were gathered including 12 countries, which basically covered 80% of the global rice growing areas (Fig. 1). Of these, the majority (65.17%) of the data were obtained from India (33.23%) and China (31.94%). The remaining data were obtained from various countries: Thailand (11.77%), Vietnam (10.61%), Bangladesh (3.80%), Korea (2.54%), Cambodia (2.03%), Pakistan (1.02%), and a combination of Spain, the Philippines, Sri Lanka, and Japan (3.05%). The majority of the data were obtained from South Asia (38.58%) and East Asia (34.62%), followed by Southeast Asia (25.03%). Publication years ranged from 1995 to 2021, and more than half of all observations were collected between 2012 and 2020.

Metadata (when available) pertaining to publication references, study region, crop, climatic, adaptation strategies, and methodological were recorded. Publication reference–relevant metadata included title, authors, date of publication, and type. Study region factors included country, region, and city. Crop-relevant metadata included rice varieties, rice cultivars, cropping systems, and changes in rice yield (%). In this study, rice varieties refer to different classifications of rice, including Indica rice, Japonica rice, and Hybrid rice, with sample sizes included in the meta-analysis being

1430, 440, and 753, respectively. Unlike the former, rice cultivars refer to rice that has been artificially bred, artificially selected, widely grown in agriculture, and mainly include specific cultivars of Indica, Japonica, and hybrid rice, such as International Rice 8 (IR8) and Khao Dawk Mali 105 (KDML105). Climatic relevant metadata included climate scenarios, changes in mean annual temperature (°C), changes in mean annual precipitation (%), and changes in CO_2 concentration (ppm). Adaptation strategy–relevant metadata included with/without changing varieties, fertilizer management, irrigation management, and change of planting dates. Finally, methodologically relevant metadata such as research methods, crop models, and climate models were also noted, and future horizons and the reference periods were considered. Table 1 presents the descriptive statistics of the main parameters used for meta-analysis.

2.3 Statistical analysis

The objective of the statistical analysis was to estimate the relative change in rice yield caused by climate change (i.e., changes in temperature, precipitation, and atmospheric CO_2 concentration) and various agronomic adaptation strategies (i.e., with/without changing varieties, adjusting fertilization, adjusting irrigation, and changing planting date).

The analysis employed multilevel regression modeling including a random effect associated with different studies. The inclusion of the random effect allows for heterogeneity between different studies included in the database. Multilevel regressions are mixed-effect models, which enable examining observations derived from different climate scenarios, methods, and cropping systems (Qian et al. 2010; Eagle et al. 2017). For mixed-effect models, different variables were tested as fixed effects (i.e., mean temperature change, mean precipitation change, CO_2 concentration, with/without changing varieties, fertilization changes, irrigation changes, and planting date changes) and as random effects (i.e., publication references, countries, climate scenarios, climate models, crop models, projected year, and cropping systems). Linear mixed-effects models were fitted to the data using the package lme4 in R 4.0.5 (Pinheiro and Bates 2006; Team RC 2013). The mixed-effect model for rice was defined by:

$$Y_{\mathrm{ij}} = \alpha_0 + \alpha_T * T_{\mathrm{ij}} + \alpha_P * P_{\mathrm{ij}} + \alpha_C * C_{ij} + \alpha_{TC} * T_{\mathrm{ij}} * C_{ij} + \alpha_V * V_{ij} + \alpha_F * F_{ij} + \alpha_I * I_{\mathrm{ij}} + \alpha_D * D_{\mathrm{ij}} + \varepsilon_{\mathrm{ij}} \quad (1)$$

where Y_{ij} is the jth value of the relative change in rice yield (in %) in study i, α_{T} corresponds to the effect of a 1 °C increase of temperature has on yield in study i, α_{P} is a parameter describing the effect of a 1% increase in precipitation on yield, α_{C} is a parameter describing the effect of increasing CO_2 by one ppm, α_{TC} is a parameter that describes the interaction of temperature and CO_2 concentration on rice yields, α_{V} is a parameter corresponding to the effect changing varieties has on adaptation to climate change, α_{F} is a parameter describing the effect a 1% increase in fertilization has on yield, α_{I} is a parameter describing the effect a 1% increase in irrigation has on yield, and α_{D} is a parameter describing the effect planting 1 d earlier has on yield. The variables T_{ij}, P_{ij}, and C_{ij} are the jth values of mean temperature change, mean precipitation change, and CO_2 concentration obtained by study i. Variable V_{ij} is a dummy variable

Table 1 Descriptive statistics of variables in meta-analysis.

Variables	n	Mean	Min	Max	Std. dev
Rice yield change (%)	2949	−5.03	−71	108	19.338
Temperature change (°C)	2949	2.41	−6	12	1.867
Rainfall change (%)	2949	5.57	−68	110	14.062
CO_2 concentration (ppm)	2949	122.13	0	556	151.435
Changing varieties (yes = 1, no = 0)	2623	0.06	0	1	0.237
Changing fertilizer (%)	2623	12.28	−50	225	37.633
Changing irrigation (%)	2623	4.43	−42	230	18.668
Changing planting (d)	2623	3.51	−40	75	15.617

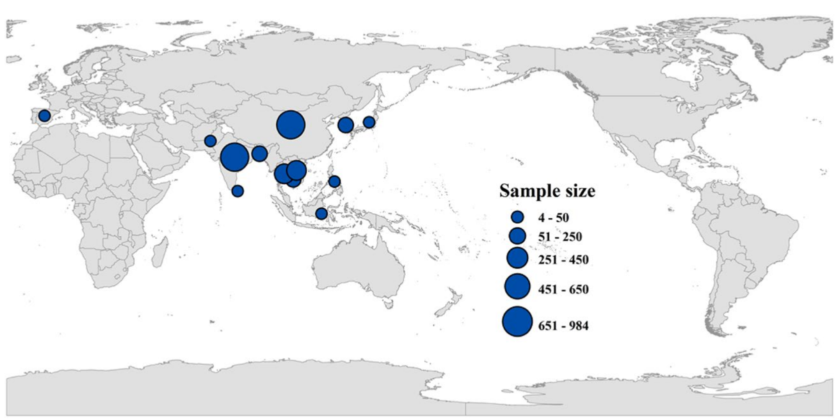


Fig. 1 Global distribution of study sites where data used for the meta-analysis were collected.

that equals 1 in situations where varieties are changed, and that equals 0 otherwise. The variables F_{ij}, I_{ij}, and D_{ij} are the *j*th values of fertilization change, irrigation change, and planting date change obtained by study *i*. The term ε_{ij} is a random error, distributed according to a Gaussian distribution ε_{ij} ~N (0, δ_{ij}^2), describing intra-study variability, where δ_{ij} is the residual standard deviation for study *i*. The values of δ_{ij} are assumed to be proportional to the standard deviations extracted from the selected articles, thus assigning less weight to the most uncertain studies.

2.4 Agronomic adaptation strategies evaluation

The *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change suggests several adaptation strategies to cope with potential climate change: altering planting dates, switching to high-temperature-tolerant varieties, and breeding new varieties (Howden et al. 2007). These measures are assumed to be helpful while cropping systems and field management processes are kept constant at the normal level in the future. Optimizing irrigation, controlling diseases, and improving crop management practices were also suggested (Kapetanaki and Rosenzweig 1997; Lashkari et al. 2012). In this study, the following strategies were evaluated separately as adaptation strategies to eliminate the projected impacts of climate change: changing varieties, adjusting fertilization, adjusting irrigation, and altering planting dates. For rice, the projected yields indicated the required scale of adaptation strategies that need to be adopted in future climate change scenarios in the study area.

Existing studies suggested that no single adaptation strategy fits all future challenges (i.e., negative environmental impact); therefore, a combination of adaptation strategies would likely produce strong co-benefits (Millar et al. 2007; Boonwichai et al. 2019a, b; Siddiqua et al. 2019). These co-benefits could focus on the acceptability of adaptation options in terms of factors that are important to stakeholders and their perceptions of synergies and barriers. The combination of adaptation strategies is expected to address resource constraints such as irrigation water and fertilizer (because of environmental concerns) while increasing rice yields and enhancing climate resilience. In this research, adaptation strategy combination options are explored to meet increasing yield requirements under future climate change. The emphasis is on identifying strategic combinations that require the minimal alteration to current agricultural management strategies, in alignment with the optimization strategies proposed in previous literature (Hitaj et al. 2019; He et al. 2021). Optimization was conducted for each grid by solving the nonlinear programming problem as follows:

$$Min\|D_k\| \tag{2}$$

$$\text{s.t. } \alpha_T T_k + \alpha_P P_k + \alpha_C C_k + \alpha_{TC} T_k C_k + \alpha_V V_k + \alpha_F F_k + \alpha_I I_k + \alpha_D D_k = Y_k \tag{3}$$

$$\sum_k Y = Y_{goal} \tag{4}$$

$$V_k = 0\, or\, 1 \tag{5}$$

where D_k is the number of days for the *k*-th grid to alter the planting date. α_T, α_P, α_C, α_{TC}, α_V, α_F, α_I, and α_D represent the marginal effects of temperature, precipitation, CO_2 concentration, temperature and CO_2 concentration, changing varieties, adjusting fertilization, adjusting irrigation, and altering planting dates on rice yields, respectively. T_k, P_k, and C_k are the *k*-th grid values of mean temperature change, mean precipitation change, and CO_2 concentration, respectively. V_k represents with/without changing varieties for the *k*-th grid, which is a dummy variable that equals 1 in situations where changing varieties is present, and that equals 0 otherwise. F_k and I_k represent the amount of fertilization change and irrigation change for the *k*-th grid, respectively. The targets of the first draft of the post-2020 global biodiversity framework (Cbd 2020)—a proposal to minimize nutrient overload that may harm the environment—recommend reducing the use of nutrients, such as nitrogen, by half. Thus, in this study, F_k is set to be reduced by 50%. In reference to the United Nations World Water Development Report (UN Water 2018) and the Planetary Boundaries framework (Sandin et al. 2015), a global target for reducing the environmental impact of water resources is identified, with a set I_k of 40% reduction. Y_k represents the change in rice yields for the *k*-th grid. Y_{goal} is the goal of rice yield increase, which is set to be 10%.

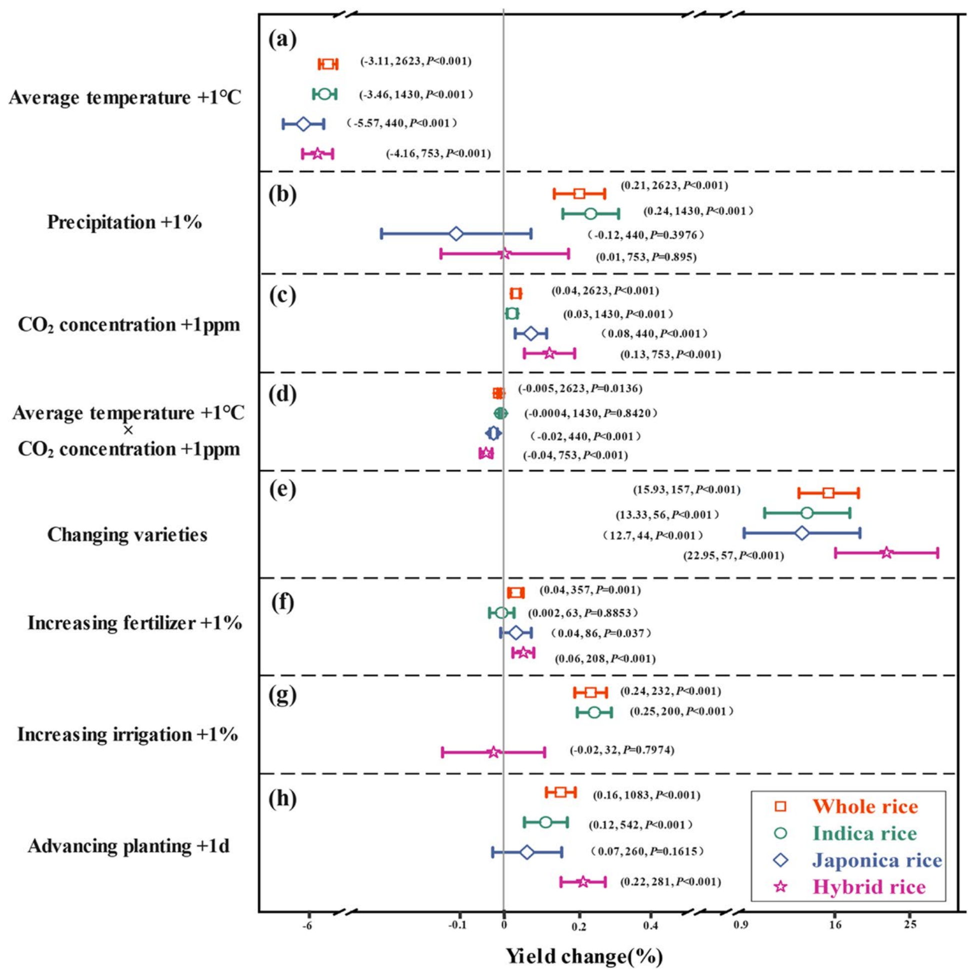
3 Results

3.1 Impact quantification of rice yield under climate change and agronomic adaptation strategies

The impacts of climate change and four implemented agronomic adaptation strategies on rice yields are assessed in a dataset containing 12 rice-producing countries (Fig. 2 and Supplementary Table 1). These represent most global major rice cultivating regions (Fig. 1). The results indicated significant ($p < 0.05$) negative impacts of warming, with whole rice (WR, whole rice sample, including indica, japonica and hybrid rice, same as below) yield loss of 3.11% per unit increase in temperature (°C) (Fig. 2a). Rainfall and CO_2 had significant positive effects on WR yield, which increases by 0.21% and 0.04%, respectively (Fig. 2b and c). The marginal effect of warming on WR yield was much higher than that of elevated CO_2. At the same time, the interaction between temperature and CO_2 concentration on WR yields was significantly negative, which indicated the positive effect of CO_2 on yield may partly be offset by an increase in temperature (Fig. 2d). The overall sensitivity of WR yield to a one-unit increase in one of the factors taken individually is consistent with other studies (Challinor et al. 2014; Makowski et al. 2020). The sample of each rice cultivar also had affecting factors that were significant but not generalizable. The temperature rise was significantly and negatively correlated with yield in Indica, Japonica, and Hybrid rice, but at varying magnitudes (Fig. 2a). Japonica rice yield decreased by 5.57% per one unit of increase in temperature (℃) and was lower than the other two rice varieties, implying that this variety is more vulnerable to climate warming. Rainfall and CO_2 were significant factors for Indica rice and were positively correlated with yield, achieving increases of 0.24% and 0.03%, respectively (Fig. 2b and c).

Agronomic adaptation strategies (changing varieties, adjusting fertilization and irrigation, as well as altering planting dates) had strong effects on rice yield (Fig. 2e–h and Supplementary Tables 2, 3, 4). Changing varieties increased WR yield significantly by 15.93% compared to no variety change. Adding fertilizer and irrigation significantly and positively affected WR yield. However, the marginal effect of fertilizer addition on WR yield was lower than that of irrigation. WR yield increased by 0.04% for each additional 1% of fertilizer. Early planting had a significantly positive impact on WR yield, which increased by 0.16% per day of advanced planting. The effects of agronomic adaptation strategies were slightly different among rice varieties, where the absence of a significant adaptation effect was probably at least partly caused by limited data availability. Changing varieties had a significantly positive effect on three rice varieties compared to not changing varieties. Hybrid varieties generally showed a greater yield response to changing varieties than the other two rice varieties; yield significantly increased by 22.95% (Fig. 2e). The impact estimate of increasing fertilization was only positive for Japonica and Hybrid rice with rice yield increases of 0.04% and 0.06%, respectively (Fig. 2f). Increasing irrigation only had a significantly positive effect on Indica yield (Fig. 2g). Early planting is the most effective option for both Indica and Hybrid rice, and yields will increase by 0.12% and 0.22%, respectively (Fig. 2h). It is worth noting

Fig. 2 Percentage changes in rice yield in response to climate change (**a**–**d**) and various agronomic adaptation strategies (**e**–**h**). **a**–**c** yield changes (%) with increasing temperature (**a**), increasing rainfall (**b**), and elevated CO_2 concentration (**c**); **d** yield change (%) in response to interactions of increased temperature with increased CO_2 concentration (**d**); **e**–**h** yield changes (%) with changing varieties (**e**), increasing fertilizer (**f**), increasing irrigation (**g**), and advancing planting (**h**). Values are means (hollow symbol) with ± 95% confidence intervals (thick lines). Parameter value, the numbers of observations and *p*-values are shown in brackets. The square, circle, diamond, and star symbols represent whole rice, Indica, Japonica, and Hybrid rice, respectively, the colors of which are orange, green, blue, and purple, respectively.



that changing varieties was the most effective agronomic adaptation strategy distinguished in the study, followed by increased irrigation. These results also inferred that changing the variety to adapt to climate change was a better opportunity, as it was effective for all three rice varieties.

3.2 Impacts of projected climate change on global rice yield

Predicted future climate changes might further aggravate climate risks to rice yield. Global average WR yield showed a continuously decreasing trend from the baseline period (2015–2020) to medium-term periods (the 2020s, 2030s, and 2040s) in all scenarios (Fig. 3). The projections indicate an overall negative effect of climate change on rice yield, with a projected decrease of average WR yield of 0.10% (for the 2020s, SSP3-7.0) and 2.11% (for the 2040s, SSP5-8.5) from the baseline period. The decrease in global average WR yields will become noticeable by the 2030s and further intensify by the 2040s, in particular under SSP5-8.5. These findings indicate that climate change, i.e., the inclusion of temperature, rainfall, and CO_2 effects, decreased average WR yield by 0.10% (average rice yield of 5322 kg/ha under future climate change), 0.79% (5266 kg/ha), and 1.75% (5227 kg/ha) in the 2020s, 2030s, and 2040s, respectively, under the SSP3-7.0 scenario. The projected increase in rainfall and CO_2 fertilizer effect partially compensated (but did not fully offset) the negative impacts of rising temperature on WR yields. The decrease in average WR yield is substantial under SSP5-8.5 (from −0.41% (5320 kg/ha) to −2.11% (5216 kg/ha) relative to baseline climate) compared to SSP2-4.5 (from −0.50% (5321 kg/ha) to −1.72% (5226 kg/ha)) and SSP3-7.0 (from −0.10% (5322 kg/ha) to −1.75% (5227 kg/ha)). The primary factor that aggravates the yield reduction is the higher temperature (Fig. 2a). These changes reflect further losses in WR yield in northern temperate regions (southern China, northern India, and Europe) and tropical regions (sub-Saharan Africa and southern Brazil). For example, WR yields in India, China, and Brazil are projected to decrease by 2.05% (3559 kg/ha), 2.50% (8305 kg/ha), and 3.62% (4862 kg/ha), respectively, by the 2040s under SSP5-8.5. Given that these countries alone account for the majority of global rice production, such synchronized production shocks are likely to tremendously impact global cereal markets.

The spatial heterogeneity of the effects of climate change on rice yield was related to rice varieties. The average yields of Indica, Japonica, and Hybrid rice consistently show negative changes compared with the baseline period in all scenarios (Supplementary Fig. 2 and 3). The results indicate markedly more pessimistic yield responses for Japonica, with the yield reduction of 5.26% (6801 kg/ha) in the 2040s under the SSP5-8.5 scenario, followed by Hybrid and Indica rice, with yield reductions of 2.35% (5185 kg/ha) and 2.24% (3646 kg/ha), respectively. The main contributing factor to inter-cultivar difference is the higher marginal effect of warming for Japonica. Compared to the tropical Indica planting region, the "emergence" of negative climate

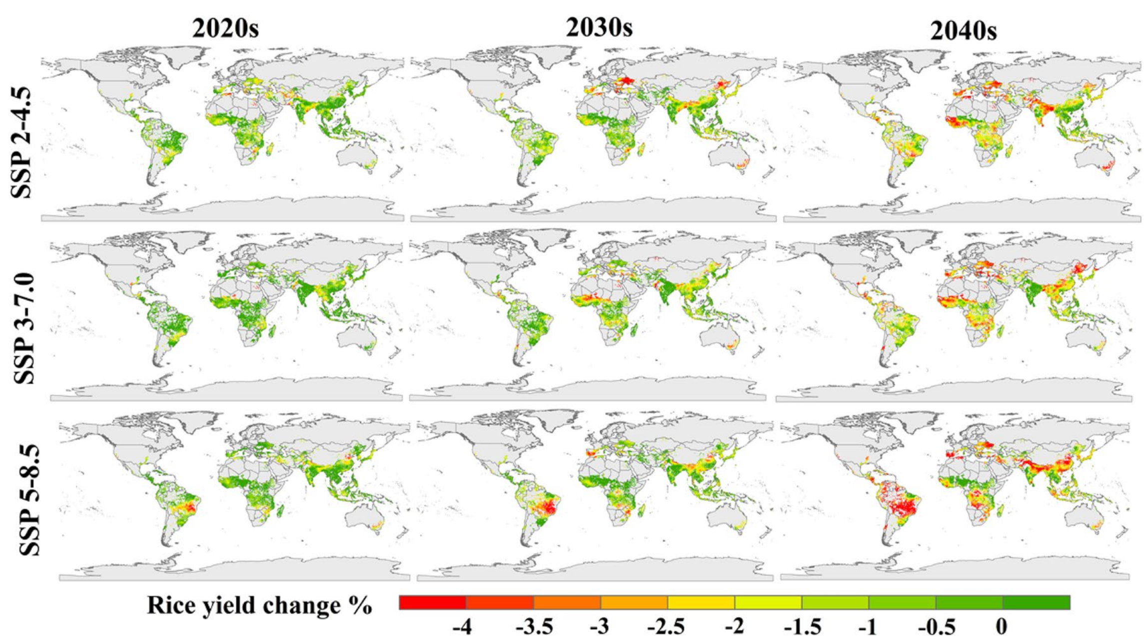


Fig. 3 Projected rice yields compared with the baseline (2015–2020) in the 2020s, 2030s, and 2040s under SSP2-4.5, SSP3-7.0, and SSP5-8.5.

impacts occurs earlier for most temperate Japonica planting regions (before 2030). The gap between the magnitude of yield loss of Japonica and Indica rice widened significantly from the 2030s onwards. The results indicate that the average yield of temperate Japonica planting regions and tropical Indica planting regions decreased by 1.03% (7134 kg/ha) and 0.41% (3673 kg/ha), respectively, in the 2020s under the SSP5-8.5 scenario, while it decreased by 2.35% (6994 kg/ha) and 1.13% (3625 kg/ha), respectively, in the 2030s. Similarly, Japonica rice is likely to experience a stronger reduction than Hybrid rice in the same regions, assuming that Hybrid rice achieves global extension of cultivation. The average yield of Hybrid rice will decrease by 0.49% (5283 kg/ha) in the 2030s under the SSP5-8.5 scenario. Similarly, Indica rice is more vulnerable to climate change compared to Hybrid rice. These findings suggest that in the future, with increasing temperatures, Hybrid rice will become an increasingly attractive option, which also implies that greater rice diversity will be beneficial to finding suitable varieties to cope with climate change.

3.3 Agronomic adaptation strategies required for improving global rice resilience

Changing varieties will be required in most rice cultivation areas to combat the negative effects of climate change. The global WR planting grids requiring a change of varieties are projected to continuously expand to mitigate the shock of climate change on WR yield from the baseline period to medium-term periods (Fig. 4a). 49.31%, 75.23%, and 90.79% of current rice planting grids would be required to change varieties until the 2020s, 2030s, and 2040s, respectively, under the SSP3-7.0 scenario. Expanding regions are mainly located in globally important rice production regions, such as southern India, sub-Saharan Africa, and Brazil. These regions start to be negatively affected by climate change from the 2030s onwards (Fig. 3). For different rice varieties, regions are affected differently. Japonica and Indica rice require a higher level of adaptation strategies compared with Hybrid rice (Supplementary Figs. 4 and 8). The results show that almost all temperate Japonica planting grids and Indica rice planting grids will need to change varieties by the 2040s under the SSP3-7.0 scenario. The climate-induced yield response for Japonica rice and Indica rice is markedly more pessimistic compared to Hybrid rice. In contrast, changing varieties is more urgent for Japonica rice and Indica rice to adapt to climate change.

Adaptation to climate change will require an increase in fertilization and irrigation in the future. The results indicate that fertilizer and irrigation would continue to increase to improve climate resilience in three future stages in all scenarios (Fig. 4b and c). The average fertilizer application is projected to increase by 8.98%, 20.17%, and 51.22% by the 2020s, 2030s, and 2040s, respectively, under the SSP5-8.5 scenario, which would offset 0.41%, 0.86%, and 2.11% of the loss of the average rice yields due to climate change in the future, respectively. Because the marginal effect of irrigation on WR yield is greater than that of fertilization, the increase in irrigation was much lower than that of fertilization (Fig. 2e and Supplementary Fig. 5, 6, and 9). The average irrigation consumption would increase by 1.5%, 3.36%, and 8.54% by the 2020s, 2030s, and 2040s, respectively, under the SSP5-8.5 scenario. Although irrigation is more efficient in increasing rice yield, it may be limited by the cost and availability of water resources, especially in developing countries. Major rice-producing countries such as Pakistan, Brazil, Bangladesh, and China projected increased fertilizer application by 97.47%, 90.56%, 86.72%, and 62.69%, respectively. Increased fertilizer application for climate change adaptation will result in a 3.37% increasing in average rice yields and offset the negative impacts of future climate change. These values exceed the global average in the 2040s under the SSP5-8.5 scenario. Irrigation strategies exhibited similar spatial heterogeneity. Notably, the increase of fertilizer application for Japonica rice is 130.75% in the 2040s under the SSP5-8.5 scenario (Supplementary Fig. 5), which is approximately three times higher than that of Hybrid rice (Supplementary Fig. 9). It can be concluded that Japonica rice requires a higher amount of fertilization to adapt to climate change as it is more sensitive to climate change. Overall, adaptation to climate change through more input and resources may be accompanied by exacerbating trade-offs between rice yield and the environment.

Early planting could effectively mitigate the negative impacts of climate change on rice yield. The planting dates are projected to advance by 3, 5, and 13 days on average relative to the original baseline planting dates in the 2020s, 2030s, and 2040s, respectively, under the SSP5-8.5 scenario (Fig. 4d). Globally important rice production regions (i.e., China, India, and Brazil) are predicted to alter planting dates to earlier dates compared to the global average for SSP5-8.5. Even under the low warming scenario of SSP2-4.5, an advance of 11 days on average of the rice planting date will be required in the 2040s, mainly covering parts of India and parts of West Africa. It is worth noting that the average days of advance sowing are earlier for Indica rice compared to Hybrid rice. For example, Indica rice and Hybrid rice will advance by 16 and 5 days, respectively, in the 2040s under the SSP3-7.0 scenario (Supplementary Fig. 7 and 10). The main explanation is that the early planting strategy of Hybrid rice is more effective than in Indica rice. The results also indicate that in regions such as Southeast Asia and Sub-Saharan Africa, Indica rice planting dates are even more advanced than those of Hybrid rice. Therefore, it can be inferred that altering planting dates coupled with choosing more suitable varieties is conducive to improving global rice resilience.

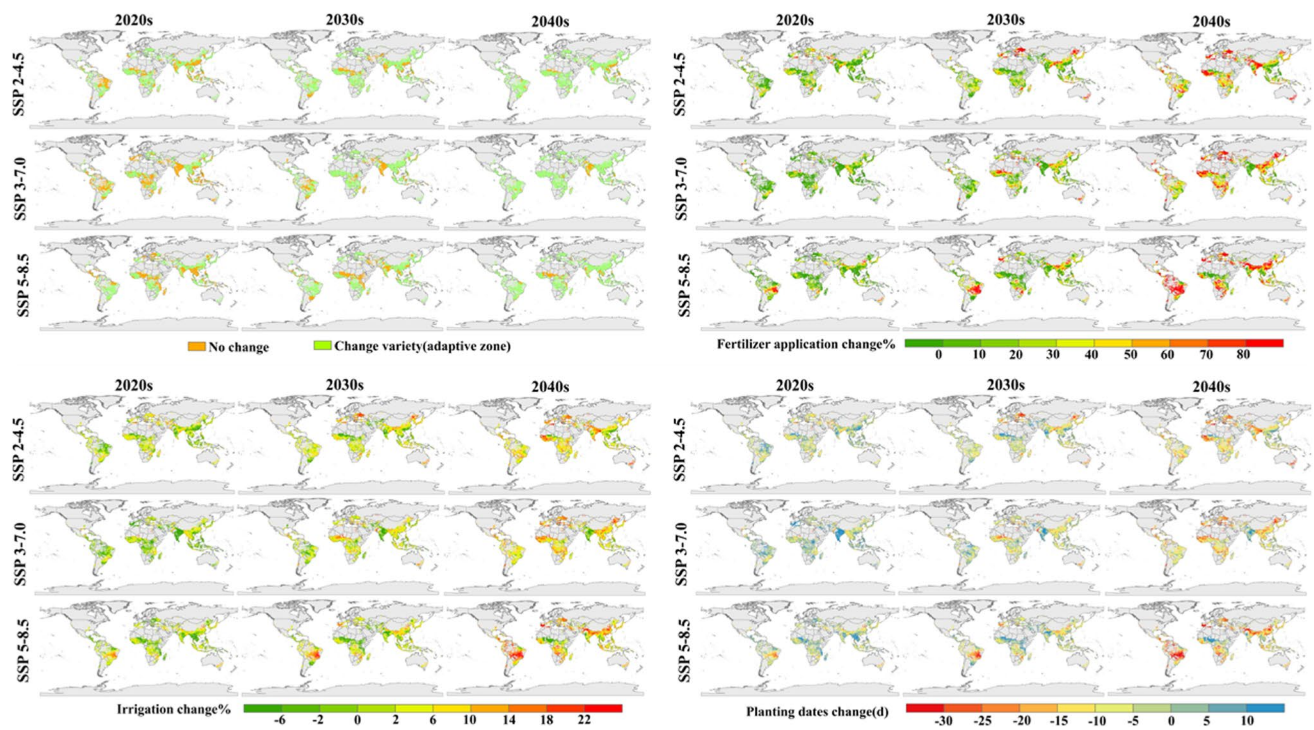


Fig. 4 Changing varieties (**a**), adjusting fertilization (**b**), adjusting irrigation (**c**), and altering planting date (**d**) compared with the baseline (2015–2020) in the 2020s, 2030s, and 2040s under SSP2-4.5, SSP3-7.0, and SSP5-8.5.

Combining all agronomic adaptation strategies considered in this study can improve global rice resilience without worsening the environmental boundaries of nitrogen and water resources. The results of the optimized combination of adaptation strategies are displayed in Supplementary Fig. 14. Changing varieties coupled with altering planting dates can achieve a 10% increase in global WR yield while reducing fertilizer by 50% and irrigation by 40%. For instance, almost all global WR planting grids need to change varieties in the 2040s under the SSP5-8.5 scenario, and portions of regions require earlier planting. It is worth noting that certain regions exhibit delayed planting, mainly as they are relatively less negatively affected by climate change, and under these conditions, the target of increasing yield is already exceeded by only changing varieties. This situation becomes more apparent in the 2020s and 2030s, implying that a combination of changing varieties and early planting would likely produce strong co-benefits. By and large, Indica rice follows a similar pattern of adaptation strategy combinations (Supplementary Fig. 11). However, the optimized combination of adaptation strategies adopted by Hybrid rice is not consistent with Indica rice. The results suggest that for Hybrid rice, altering planting dates or changing varieties can improve climate resilience in conditions of reduced fertilization and irrigation (Supplementary Figs. 12 and 13). The main explanation is that these two adaptation strategies for Hybrid rice are more effective than for Indica rice, especially for changing varieties.

4 Discussion

4.1 Climate change will inevitably challenge future rice yield

Overall, future climate risks to rice yields will exacerbate. Rice yields show a significant reduction under future time periods. The yields are expected to be decreased by 0.41%, 0.86%, and 2.11% in the 2020s, 2030s, and 2040s, respectively, compared to the baseline yield under the SSP5-8.5 scenario (Fig. 3). A projected increase in temperature relative to the baseline period could be the contributing major factor to lower yield, which affects rice yield by reducing grain-filling duration and enhancing respiration losses (Shrestha 2014; Wang et al. 2015). Moreover, higher temperatures enhance evapotranspiration, which increases evaporative demand. Because of the shift in precipitation pattern, the required water remains unmet, and therefore, the yield decreases (Shrestha 2014; Deb et al. 2016a, b). The results indicate that the global average WR yield decline is higher in the SSP5-8.5 scenario than in the SSP2-4.5 scenario, despite the higher CO_2 concentration (Fig. 3). The potential beneficial effect of elevated CO_2 levels on rice yield has been well-documented (Lobell et al.

2011; Venkateswarlu and Rao 2013), but the CO_2 fertilization effect on rice yield was not sufficient to offset the adverse effect of warming (Satapathy et al. 2014a, b; Wang et al. 2015; Singh et al. 2019). Substantial differences were found in the sensitivity of rice varieties to climate change, suggesting that climate change impact assessment without considering varieties' adaptability may result in biased estimations (Shew et al. 2020). For example, Japonica rice has a markedly more pessimistic yield projection, with a decrease exceeding −5.26% in the 2040s under the SSP5-8.5 scenario, followed by Hybrid and Indica rice exceeding −2.35% and −2.24%, respectively. It is noteworthy that our study primarily focuses on the overall impact of general climate factors such as temperature, precipitation, and carbon dioxide on rice yield. However, an increasing number of researches have revealed that extreme climates such as droughts cause significant and timely damage to crop production and food system infrastructure (Lesk et al. 2016). Kang et al. (2021) indicated that considerable decreases in rice yield up to 1.5 tons/ha in the Vietnam Central High Plain region could be expected resulting from reduced precipitation by about 34% during drought years. With climate extremes expected to become more common in the future (Battisti and Naylor 2009), further research on the impacts of climate extremes on crop production will help to design effective interventions.

Climate change is predicted to affect rice yield differently depending on the region. Major high-value regions of declining WR yields are projected to be concentrated in large global rice production and trading countries, such as India, China, and Brazil. Synchronized production shocks among these large trading countries will directly impact urban consumers, grain producers, as well as poor households that will have to spend a large share of their income on staple foods (Tigchelaar et al. 2018). These findings highlight challenges for rice system adaptation faced by climate change. Without specific climate agronomic adaptation strategies to improve rice climate resilience, there may be little opportunity to increase rice yield and stabilize food markets in the face of projected yield declines. Climate adaptation is thus a high priority, yet an unattained goal in rice production.

4.2 Urgency and large opportunities for climate adaptation in rice variety diversity

Promoting the diversity of varieties for enhanced climatic resilience of the rice systems is paramount. Variety diversification (i.e., substituting one variety for another) can be a rational and cost-effective way to increase the resilience of the agricultural system under climate change (Lin 2011). The results of this study indicate that 49%, 75%, and 90% of the current rice planting grids would require a change of varieties until the 2020s, 2030s, and 2040s, respectively, under the SSP3-7.0 scenario. The urgency of variety change adaptation would be further exacerbated under the SSP5-8.5 scenario. In addition, we further comprehensively analyze the impact of varying degrees of rice variety change due to genetic gain on rice yield losses in the next three decades. When only 20% of the rice planting areas change varieties, rice yield losses caused by climate change will be reduced by 0.24 to 49.86%. With further increases to 50 and 75% of rice planting areas, the rice yield losses are reduced by 19.15 to 80.84% and 50.14 to 93.24%, respectively. Shifting to 100% variety change across the entire region is expected to result in increased yields, as our findings indicate that changing varieties in 90% of the region is already fully mitigating the rice yield losses induced by climate change. The findings that climate change impacts rice yields and the urgency of adapting by changing varieties are consistent with the recent findings of Zhang et al (2022). Zhang et al. (2022) showed that the current Chinese single rice would require a change of varieties in approximately 80% of cropping areas before the 2040s under RCP4.5, and variety adaptation is even more urgent under RCP8.5. Warming will accelerate rice growth and increase the risk of heat stress, but there is variability in the response of different rice varieties to climate change (Supplementary Fig. 2 and 3). It is beneficial to select varieties with climatic advantages for adaptation as various rice varieties have different climatic resilience. The introduction of short-duration crop varieties and planting early/late-maturing varieties may help curtail the adverse impacts of climate risk (Sonune and Mane 2018). Similarly, adopting heat-tolerant varieties can address the issue of excess heat (Aryal et al. 2020). However, the potential for crop diversity adaptation depends on the varieties that will become available in the future. Previous studies have shown that for low levels of warming such as in SSP1-2.6, 85% of global cropland areas can be supplied with adapted varieties from the pool of currently existing varieties. However, 39% of global cropland areas will require new varieties for SSP5-8.5 by the end of the century (Zabel et al. 2021). For these areas, region-specific breeding efforts are required to allow for a successful adaptation to climate change (Challinor et al. 2016). The results indicate that under the SSP5-8.5 scenario, the most important rice production regions in India and China would suffer severe yield losses (Fig. 3). However, Zabel et al. (2021) indicated that for rice, the most important production regions in India and China could still use existing varieties for adaptation in the future. The results suggest that variety adaptation is a large opportunity for mitigating climatic risks in rice production.

4.3 Optimized planting dates effectively improve global rice resilience

Future climate change inevitably reduces rice yields (Fig. 3). Altering planting dates is considered a useful strategy to adapt to changing climatic conditions (Ding et al. 2020). The results suggest that early planting under future climate scenarios can offset the negative effects of climate change. The average planting dates are projected to advance by 3, 5, and 13 days relative to the original baseline planting dates in the 2020s, 2030s, and 2040s, respectively, under the SSP5-8.5 scenario (Fig. 4d and Supplementary Fig. 7). This can be attributed to the matching between altered planting dates and rice-growing periods with the temporal patterns of climate change. Light, heat, and other conditions can then be better utilized, thereby avoiding yield reduction caused by climate risks (Dharmarathna et al. 2014a, b; Rajwade et al. 2018a, b). In fact, farmers can lower the negative impact of changing climate on crop yields by altering the planting dates to more favorable weather conditions, thereby improving rice production resilience. This strategy is already implemented across many regions. Previous studies indicated that 16% of more than 8000 households in 11 African countries (Hassan and Nhemachena 2008) and 5% of surveyed farmers in the Nile Basin of Ethiopia (Deressa et al. 2009)shift their planting dates to match delayed or early rainfall. However, the adaptation effectiveness of altering planting dates on yield was related to rice varieties. Rice cultivar variability for the effectiveness of altering planting dates was further investigated, and Hybrid rice was found to benefit more from earlier planting dates (Supplementary Fig. 7 and 10). It can be inferred that altering planting dates coupled with choosing suitable varieties is more conducive to adapting to climate change, which is consistent with previous studies. Ding et al. (2020) showed that for single rice in northeastern China and the Yunnan-Guizhou plateau, although early planting slowed the development rate and benefited rice yields, the rice growth duration was still shorter than the baseline period. Therefore, varieties with longer maturity should be adopted simultaneously to adapt to climate change.

4.4 More efficient ways are needed to compensate for increases in fertilization and irrigation requirements

Agricultural practices (e.g., adjusting nutrient management and changing irrigation) provide the opportunity to offset the negative impacts of climatic changes (Shrestha and Trang 2015a, b; Li and Troy 2018; Shabbir et al. 2020). The results of this study suggest that increasing fertilizer and irrigation can eliminate yield loss to enhance rice climate resilience by increasing rice productivity. It is worth noting that certain regions will require more fertilization and irrigation than the global average (Fig. 4b). For example, major rice-producing countries such as Pakistan, Brazil, Bangladesh, and China were projected to increase in fertilizer application by 97.47%, 90.56%, 86.72%, and 62.69%, respectively, in the 2040s under the SSP5-8.5 scenario. However, rice yield cannot be easily increased by more fertilization or irrigation in areas such as South Asia, where shortages of water and nutrients are the main limitations in rice production (Lobell et al. 2008). At the same time, fertilizer applications with excess nitrogen may lead to nutrient leaching, as well as increased greenhouse gas emissions, which may damage aquatic ecosystems and groundwater supplies (Millar et al. 2018). Excessive irrigation can also exacerbate water scarcity. This will exceed the environmental planetary boundaries, which is a safe operating space for humanity (Steffen et al. 2015; Conijn et al. 2018). Therefore, the use of fertilizer and irrigation can be improved by more efficient methods, such as replacing nitrogenous fertilizer with green manure, precision irrigation, rainwater collection, and a system of rice intensification. Water harvesting, an age-old practice of collecting rainwater in India, is another potential way to manage irrigation water deficit across seasons (Singh et al. 2018). The system of rice intensification has been reported to increase crop yield by more than 10% with less water consumption (i.e., 25–47% less water) in India, China (Wu et al. 2015), and Nepal (Reeves et al. 2016), compared to the traditional rice system. In addition, the results of this study show that changing varieties coupled with altering planting dates can achieve a 10% increase in global WR yield in conditions of fertilizer reduction by 50% and irrigation reduction by 40% (Supplementary Fig. 14). These results further highlight that the appropriate combination of all available adaptation strategies would allow improving rice climate resilience without worsening the environmental boundaries of nitrogen and water resources.

5 Conclusions

Developing effective agronomic adaptation strategies is paramount in safeguarding the global rice supply against the challenges posed by climate change. Our research initiates a novel approach to crafting agronomic strategies aimed at bolstering the resilience of rice production in the context of climate change. In addition, our study refines different rice varieties, which provides new knowledge for the adaptive management of rice production. Results from our research form a basis for a better understanding of rice climate resilience and agronomic adaptation strategies. Overall, warming emerges as a primary concern, exerting a substantial negative marginal impact of −3.11% on WR yield. While elevated CO_2 and increased precipitation show marginal positive effects of 0.04% and 0.21%, respectively, these alone cannot fully counterbalance the adverse effects of warming. Among the identified adaptation strategies, changing rice varieties stands out as the most impactful, with a remarkable marginal effect of 15.93% on WR yield. This suggests that breeding and adopting rice varieties resilient to changing climatic conditions can significantly contribute to maintaining or even enhancing yields in the face of climate challenges. The nuanced results across three rice varieties (Indica, Japonica, and Hybrid rice) emphasize the need for tailored adaptation strategies based on the characteristics and resilience of each variety. A one-size-fits-all approach may not suffice, and specific measures must be considered for different rice types to optimize their response to changing climatic conditions. In the absence of adaptation strategies, future climate changes might further aggravate climate risks to rice yield. To offset WR yield losses from future climate change, large rice planting areas will need to change varieties, increase fertilizer and irrigation inputs, or advance planting. This analysis further highlights that the appropriate combination of four adaptation strategies can tackle the negative impacts of climate change without worsening the environmental boundaries of nitrogen and water resources. To meet the food demands of an estimated 9.7 billion people by 2100, further research is imperative. Future studies should delve deeper into understanding rice yield responses to climate change and explore adaptive options to enhance the resilience of rice to evolving climatic conditions. This comprehensive approach will contribute to a more sustainable and resilient global rice production system.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s13593-024-00963-7.

Authors' contributions Zhang Yali and Wu Feng: conceptualization, methodology, and software. Li Saiya and Zhou Qing: data curation and writing—original draft preparation. Li Saiya: visualization and investigation. Zhang Yali: supervision. Wu Feng and Zhou Qing: software and validation. Zhang Yali and Li Saiya: writing—reviewing and editing

Funding This study was funded by the National Natural Science Foundation of China (no. 31861143015 and no.4227071576).

Data availability The data will be available from the corresponding author upon reasonable request.

Code availability Not applicable

Declarations

Conflict of interest The authors declare no competing interests.

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

References

Acharjee TK, van Halsema G, Ludwig F, Hellegers P, Supit I (2019) Shifting planting date of Boro rice as a climate change adaptation strategy to reduce water use. Agr Syst 168:131–143. https://doi.org/10.1016/j.agsy.2018.11.006

Akinbile CO, Ogunmola OO, Abolude AT, Akande SO (2020) Trends and spatial analysis of temperature and rainfall patterns on rice yields in Nigeria. Atmos Sci Lett 21(3):e944. https://doi.org/10.1002/asl.944

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. ESA Working Paper No. 12–03. https://doi.org/10.22004/ag.econ.288998

Ali A, Erenstein O (2017) Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. Clim Risk Manag 16:183–194. https://doi.org/10.1016/j.crm.2016.12.001

Arunrat N, Pumijumnong N, Sereenonchai S, Chareonwong U, Wang C (2020a) Assessment of climate change impact on rice yield and water footprint of large-scale and individual farming in Thailand. Sci Total Environ 726:137864. https://doi.org/10.1016/j.scitotenv.2020.137864

Aryal JP, Sapkota TB, Khurana R, Khatri-Chhetri A, Rahut DB, Jat ML (2020) Climate change and agriculture in South Asia: adaptation options in smallholder production systems. Environ Dev Sustain 22(6):5045–5075. https://doi.org/10.1007/s10668-019-00414-4

Babel MS, Agarwal A, Swain DK, Herath S (2011a) Evaluation of climate change impacts and adaptation measures for rice cultivation in Northeast Thailand. Clim Res 46(2):137–146. https://doi.org/10.3354/cr00978

Bandumula N (2018) Rice production in Asia: key to global food security. P Natl A Sci India B 88:1323–1328. https://doi.org/10.1007/s40011-017-0867-7

Battisti DS, Naylor RL (2009) Historical warnings of future food insecurity with unprecedented seasonal heat. Science 323(5911):240–244. https://doi.org/10.1126/science.1164363

Boonwichai S, Shrestha S, Babel MS, Weesakul S, Datta A (2019a) Evaluation of climate change impacts and adaptation strategies on rainfed rice production in Songkhram River Basin, Thailand. Sci Total Environ 652:189–201. https://doi.org/10.1016/j.scitotenv.2018.10.201

Cbd (2020) Zero draft of the post-2020 global biodiversity framework. Convention on Biological Diversity, Montreal, Canada. https://www.cbd.int/article/2020-01-10-19-02-38

Challinor AJ, Wheeler TR, Craufurd PQ, Ferro CA, Stephenson DB (2007) Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures. Agr Ecosyst Environ 119(1–2):190–204. https://doi.org/10.1016/j.agee.2006.07.009

Challinor AJ, Watson J, Lobell DB, Howden SM, Smith DR, Chhetri N (2014) A meta-analysis of crop yield under climate change and adaptation. Nat Clim Change 4(4):287–291. https://doi.org/10.1038/nclimate2153

Challinor AJ, Koehler A, Ramirez-Villegas J, Whitfield S, Das B (2016) Current warming will reduce yields unless maize breeding and seed systems adapt immediately. Nat Clim Change 6(10):954–958. https://doi.org/10.1038/nclimate3061

Chaowiwat W (2016) Impact of climate change assessment on agriculture water demand in Thailand. NUEJ 11(1):35–42. https://doi.org/10.14456/nuej.2016.6

Chaowiwat W, Sarinnapakorn K, Weesakul S (2019) Future changes in extreme rainfall over Thailand using multi-bias corrected GCM rainfall data. J Clim Chang Sci 9, 30-53. https://www.researchgate.net/publication/333835178

Chun JA, Li S, Wang Q, Lee W, Lee E, Horstmann N, Park H, Veasna T, Vanndy L, Pros K (2016a) Assessing rice productivity and adaptation strategies for Southeast Asia under climate change through multi-scale crop modeling. Agr Syst 143:14–21. https://doi.org/10.1016/j.agsy.2015.12.001

Conijn JG, Bindraban PS, Schröder JJ, Jongschaap R (2018) Can our global food system meet food demand within planetary boundaries? Agr Ecosyst Environ 251:244–256. https://doi.org/10.1016/j.agee.2017.06.001

Deb P, Tran DA, Udmale PD (2016a) Assessment of the impacts of climate change and brackish irrigation water on rice productivity and evaluation of adaptation measures in Ca Mau province. Vietnam. Theor Appl Climatol 125(3):641–656. https://doi.org/10.1007/s00704-015-1525-8

Deressa TT, Hassan RM, Ringler C, Alemu T, Yesuf M (2009) Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia. Global Environ Chang 19(2):248–255. https://doi.org/10.1016/j.gloenvcha.2009.01.002

Dharmarathna W, Herath S, Weerakoon SB (2014a) Changing the planting date as a climate change adaptation strategy for rice production in Kurunegala district. Sri Lanka. Sustain Sci 9(1):103–111. https://doi.org/10.1007/s11625-012-0192-2

Ding Y, Wang W, Zhuang Q, Luo Y (2020) Adaptation of paddy rice in China to climate change: the effects of shifting sowing date on yield and irrigation water requirement. Agr Water Manage 228:105890. https://doi.org/10.1016/j.agwat.2019.105890

Durand-Morat A, Bairagi S (2021) International rice outlook: international rice baseline projections 2020-2030. Research Reports and Research Bulletins. Arkansas Agricultural Experiment Station, University of Arkansas System, Little Rock, Arkansas, USA. https://scholarworks.uark.edu/aaesrb/49

Eagle AJ, Olander LP, Locklier KL, Heffernan JB, Bernhardt ES (2017) Fertilizer management and environmental factors drive N_2O and NO_3 losses in corn: a meta-analysis. Soil Sci Soc Am J 81(5):1191–1202. https://doi.org/10.2136/sssaj2016.09.0281

Fao (2007) Adaptation to climate change in agriculture, forestry and fisheries: perspective, framework and priorities. Rome, Italy. https://www.fao.org/3/au030e/au030e.pdf

Gopi G, Manjula M (2018) Speciality rice biodiversity of Kerala: need for incentivising conservation in the era of changing climate. Curr Sci India 997-1006. https://www.jstor.org/stable/26495193

Guo Y, Wu W, Du M, Bryant CR, Li Y, Wang Y, Huang H (2019a) Assessing potential climate change impacts and adaptive measures on rice yields: the case of Zhejiang province in China. Sustainability-Basel 11(8):2372. https://doi.org/10.3390/su11082372

Halder D, Kheroar S, Srivastava RK, Panda RK (2020a) Assessment of future climate variability and potential adaptation strategies on yield of peanut and Kharif rice in eastern India. Theor Appl Climatol 140(3):823–838. https://doi.org/10.1007/s00704-020-03123-5

Hassan RM, Nhemachena C (2008) Determinants of African farmers' strategies for adapting to climate change: multinomial choice analysis. AfJARE 2(1):83–104. https://doi.org/10.22004/AG.ECON.56969

He P, Feng K, Baiocchi G, Sun L, Hubacek K (2021) Shifts towards healthy diets in the US can reduce environmental impacts but would be unaffordable for poorer minorities. Nat Food 2(9):664–672. https://doi.org/10.1038/s43016-021-00350-5

Hitaj C, Rehkamp S, Canning P, Peters CJ (2019) Greenhouse gas emissions in the United States food system: current and healthy diet scenarios. Environ Sci Technol 53(9):5493–5503. https://doi.org/10.1021/acs.est.8b06828

Howden SM, Soussana J, Tubiello FN, Chhetri N, Dunlop M, Meinke H (2007) Adapting agriculture to climate change. PNAS 104(50):19691–19696. https://doi.org/10.1073/pnas.0701890104

Hu X, Huang Y, Sun W, Yu L (2017) Shifts in cultivar and planting date have regulated rice growth duration under climate warming in China since the early 1980s. Agr Forest Meteorol 247:34–41. https://doi.org/10.1016/j.agrformet.2017.07.014

Hussain S, Huang J, Huang J, Ahmad S, Nanda S, Anwar S, Shakoor A, Zhu C, Zhu L, Cao X (2020) Rice production under climate change: adaptations and mitigating strategies. Environment, climate, plant and vegetation growth(pp. 659-686). ISBN(print): 978-3-030-49731-6, Springer, https://doi.org/10.1007/978-3-030-49732-3_26

Islam ARMT, Shen S, Yang S, Hu Z, Rahman MA (2020a) Spatiotemporal rice yield variations and potential agro-adaptation strategies in Bangladesh: a biophysical modeling approach. Sustain Prod Consump 24:121–138. https://doi.org/10.1016/j.spc.2020.07.005

Jalota SK, Vashisht BB (2016) Adapting cropping systems to future climate change scenario in three agro-climatic zones of Punjab. India. J Agrometeorol 18(1):48–56. https://doi.org/10.54386/jam.v18i1.899

Kang H, Sridhar V, Mainuddin M, Trung LD (2021) Future rice farming threatened by drought in the Lower Mekong Basin. Sci Rep-UK 11(1):9383. https://doi.org/10.1038/s41598-021-88405-2

Kapetanaki G, Rosenzweig C (1997) Impact of climate change on maize yield in central and northern Greece: a simulation study with CERES-Maize. Mitig Adapt Strat Gl 1(3):251–271. https://doi.org/10.1023/B:MITI.0000018044.48957.28

Koppa N, Amarnath G (2021) Geospatial assessment of flood-tolerant rice varieties to guide climate adaptation strategies in india. Climate 9(10):151. https://doi.org/10.3390/cli9100151

Lashkari A, Alizadeh A, Rezaei EE, Bannayan M (2012) Mitigation of climate change impacts on maize productivity in northeast of Iran: a simulation study. Mitig Adapt Strat Gl 17(1):1–16. https://doi.org/10.1007/s11027-011-9305-y

Lesk C, Rowhani P, Ramankutty N (2016) Influence of extreme weather disasters on global crop production. Nature 529(7584):84–87. https://doi.org/10.1038/nature16467

Li X, Troy TJ (2018) Changes in rainfed and irrigated crop yield response to climate in the western US. Environ Res Lett 13 (6), 64031. https://orcid.org/0000-0002-4275-827X

Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JP, Clarke M, Devereaux PJ, Kleijnen J, Moher D (2009) The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. J Clin Epidemiol 62(10):e1–e34. https://doi.org/10.1016/j.jclinepi.2009.06.006

Lin BB (2011) Resilience in agriculture through crop diversification: adaptive management for environmental change. Bioscience 61(3):183–193. https://doi.org/10.1525/bio.2011.61.3.4

Liu L, Zhu Y, Tang L, Cao W, Wang E (2013) Impacts of climate changes, soil nutrients, variety types and management practices on rice yield in East China: a case study in the Taihu region. Field Crop Res 149:40–48. https://doi.org/10.1016/j.fcr.2013.04.022

Liu C, Wang L, Le Cocq K, Chang C, Li Z, Chen F, Liu Y, Wu L (2020a) Climate change and environmental impacts on and adaptation strategies for production in wheat-rice rotations in southern China. Agr Forest Meteorol 292:108136. https://doi.org/10.1016/j.agrformet.2020.108136

Lobell DB (2014) Climate change adaptation in crop production: beware of illusions. Glob Food Secur-Agr 3(2):72–76. https://doi.org/10.1016/j.gfs.2014.05.002

Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. Science 319(5863):607–610. https://doi.org/10.1126/science.1152339

Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production since 1980. Science 333(6042):616–620. https://doi.org/10.1126/science.1204531

Makowski D, Marajo-Petitzon E, Durand J, Ben-Ari T (2020) Quantitative synthesis of temperature, CO_2, rainfall, and adaptation effects on global crop yields. Eur J Agron 115:126041. https://doi.org/10.1016/j.eja.2020.126041

Millar CI, Stephenson NL, Stephens SL (2007) Climate change and forests of the future: managing in the face of uncertainty. Ecol Appl 17(8):2145–2151. https://doi.org/10.1890/06-1715.1

Millar N, Urrea A, Kahmark K, Shcherbak I, Robertson GP, Ortiz-Monasterio I (2018) Nitrous oxide (N_2O) flux responds exponentially to nitrogen fertilizer in irrigated wheat in the Yaqui Valley, Mexico. Agr Ecosyst Environ 261:125–132. https://doi.org/10.1016/j.agee.2018.04.003

Muthayya S, Sugimoto JD, Montgomery S, Maberly GF (2014) An overview of global rice production, supply, trade, and consumption. Ann Ny Acad Sci 1324(1):7–14. https://doi.org/10.1111/nyas.12540

Nelson GC, Rosegrant MW, Palazzo A, Gray I, Ingersoll C, Robertson R, Tokgoz S, Zhu T, Sulser TB, Ringler C (2010) Food security, farming, and climate change to 2050: scenarios, results, policy options. Intl Food Policy Res Inst. https://doi.org/10.2499/9780896291867

Parry ML, Canziani O, Palutikof J, Van der Linden P, Hanson C (2007) Climate change 2007-impacts, adaptation and vulnerability: working group II contribution to the fourth assessment report of the IPCC (Vol. 4). Cambridge University Press, Cambridge. https://www.ipcc.ch/report/ar4/wg2

Pinheiro J, Bates D (2006) Mixed-effects models in S and S-PLUS. ISBN(print):978-0-387-22747-4. Springer science & business media. https://doi.org/10.1007/b98882

Qian SS, Cuffney TF, Alameddine I, Mcmahon G, Reckhow KH (2010) On the application of multilevel modeling in environmental and ecological studies. Ecology 91(2):355–361. https://doi.org/10.1890/09-1043.1

Rajwade YA, Swain DK, Tiwari KN (2018a) Effect of irrigation method on adaptation capacity of rice to climate change in subtropical India. Int J Plant Prod 12(3):203–217. https://doi.org/10.1007/s42106-018-0021-3

Reeves T, Thomas G, Ramsay G (2016) Save and grow in practice: maize, rice, wheat. A guide to sustainable cereal production. Rome, Italy: UN Food and Agriculture Organization. https://hdl.handle.net/20.500.11766/67567

Rogelj J, Den Elzen M, Höhne N, Fransen T, Fekete H, Winkler H, Schaeffer R, Sha F, Riahi K, Meinshausen M (2016) Paris agreement climate proposals need a boost to keep warming well below 2 C. Nature 534(7609):631–639. https://doi.org/10.1038/nature18307

Saito K, van Oort P, Dieng I, Johnson JM, Niang A, Ahouanton K, Alognon AD, Tanaka A, Senthilkumar K, Vandamme E (2017) Yield gap analysis towards meeting future rice demand. T. Sasaki (Ed.), Achieving Sustainable Cultivation of Rice. Cultivation, Pest and Disease Management, vol. 2, Burleigh Dodds Science Publishing, Cambridge, UK (2017), pp. 157–182. https://doi.org/10.19103/AS.2016.0003.26

Sandin G, Peters GM, Svanström M (2015) Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts. Int J Life Cycle Assess 20(12):1684–1700. https://doi.org/10.1007/s11367-015-0984-6

Satapathy SS, Swain DK, Herath S (2014a) Field experiments and simulation to evaluate rice cultivar adaptation to elevated carbon dioxide and temperature in sub-tropical India. Eur J Agron 54:21–33. https://doi.org/10.1016/j.eja.2013.11.010

Seck PA, Diagne A, Mohanty S, Wopereis M (2012) Crops that feed the world 7: rice. Food Secur 4(1):7–24. https://doi.org/10.1007/s12571-012-0168-1

Shabbir G, Khaliq T, Ahmad A, Saqib M (2020) Assessing the climate change impacts and adaptation strategies for rice production in Punjab. Pakistan. Environ Sci Pollut R 27(18):22568–22578. https://doi.org/10.1007/s11356-020-08846-6

Shelley IJ, Takahashi-Nosaka M, Kano-Nakata M, Haque MS, Inukai Y (2016) Rice cultivation in Bangladesh: present scenario, problems, and prospects. J Int Coop Agric Dev 14:20–29. https://doi.org/10.50907/jicad.14.0_20

Shew AM, Tack JB, Nalley LL, Chaminuka P (2020) Yield reduction under climate warming varies among wheat cultivars in South Africa. Nat Commun 11(1):1–9. https://doi.org/10.1038/s41467-020-18317-8

Shrestha S, Trang BTT (2015a) Assessment of the climate-change impacts and evaluation of adaptation measures for paddy productivity in Quang Nam province. Vietnam. Paddy Water Environ 13(3):241–253. https://doi.org/10.1007/s10333-014-0434-2

Shrestha S (2014) Adaptation strategies for rice cultivation under climate change in Central Vietnam. Climate change impacts and adaptation in water resources and water use sectors pp 93–119. Springer. https://doi.org/10.1007/978-3-319-09746-6_6

Siddiqua A, Ahmad M, Habib N (2019) Farmers' adaptation strategies to combat climate change impacts on wheat crop in Pakistan. Pak J Agr Sci 32(2):218–228. https://doi.org/10.17582/journal.pjar/2019/32.2.218.228

Singh C, Rahman A, Srinivas A, Bazaz A (2018) Risks and responses in rural India: implications for local climate change adaptation action. Clim Risk Manag 21:52–68. https://doi.org/10.1016/j.crm.2018.06.001

Sonune SV, Mane S (2018) Impact of climate resilient varieties on crop productivity in NICRA village. J Pharm Pharmacogn 7:3210–3212. https://doi.org/10.22271/chemi.2020.v8.i6n.10885

Sridevi V, Chellamuthu V (2015) Impact of weather on rice-a review. Int J Appl Res 1(9):825–83. https://doi.org/10.17503/agrivita.v44i2.2539

Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, Biggs R, Carpenter SR, De Vries W, De Wit CA (2015) Planetary boundaries: guiding human development on a changing planet. Science 347(6223):1259855. https://doi.org/10.1126/science.1259855

Team RC (2013) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://cran.r-hub.io/doc/manuals/fullrefman.pdf

Tesfaye K, Khatri-Chhetri A, Aggarwal PK, Mequanint F, Shirsath PB, Stirling CM, Jat ML, Rahut DB, Erenstein O (2019) Assessing climate adaptation options for cereal-based systems in the eastern Indo-Gangetic Plains. South Asia. J Agr Sci-Cambridge 157(3):189–210. https://doi.org/10.1017/S0021859619000492

Tigchelaar M, Battisti DS, Naylor RL, Ray DK (2018) Future warming increases probability of globally synchronized maize production shocks. PNAS 115(26):6644–6649. https://doi.org/10.1073/pnas.1718031115

Truong An D (2020) Shifting crop planting calendar as a climate change adaptation solution for rice cultivation region in the Long Xuyen Quadrilateral of Vietnam. Chil J Agr Res 80(4):468–477. https://doi.org/10.4067/S0718-58392020000400468

UN Water (2018) The United Nations world water development report 2018. United Nations.

Venkateswarlu B, Rao V (2013) Climate change and its impact on Indian agriculture. Climate Change Modeling, Mitigation, and Adaptation pp 419–453. https://doi.org/10.1007/s41685-023-00327-1

Wang J, Wang C, Chen N, Xiong Z, Wolfe D, Zou J (2015) Response of rice production to elevated [CO_2] and its interaction with rising temperature or nitrogen supply: a meta-analysis. Clim Change 130(4):529–543. https://doi.org/10.1007/s10584-015-1374-6

Wang W, Cai C, He J, Gu J, Zhu G, Zhang W, Zhu J, Liu G (2020) Yield, dry matter distribution and photosynthetic characteristics of rice under elevated CO_2 and increased temperature conditions. Field Crop Res 248:107605. https://doi.org/10.1016/j.fcr.2019.107605

White JW, Hoogenboom G, Kimball BA, Wall GW (2011) Methodologies for simulating impacts of climate change on crop production. Field Crop Res 124(3):357–368. https://doi.org/10.1016/j.fcr.2011.07.001

Wu W, Ma B, Uphoff N (2015) A review of the system of rice intensification in China. Plant Soil 393(1):361–381. https://doi.org/10.1007/s11104-015-2440-6

Yoshida R, Fukui S, Shimada T, Hasegawa T, Ishigooka Y, Takayabu I, Iwasaki T (2015) Adaptation of rice to climate change through a cultivar-based simulation: a possible cultivar shift in eastern Japan. Clim Res 64(3):275–290. https://doi.org/10.3354/cr01320

Zabel F, Müller C, Elliott J, Minoli S, Jägermeyr J, Schneider JM, Franke JA, Moyer E, Dury M, Francois L (2021) Large potential for crop production adaptation depends on available future varieties. Global Change Biol 27(16):3870–3882. https://doi.org/10.1111/gcb.15649

Zhang L, Zhang Z, Tao F, Luo Y, Zhang J, Cao J (2022) Adapting to climate change precisely through cultivars renewal for rice production across China: when, where, and what cultivars will be required? Agr Forest Meteorol 316:108856. https://doi.org/10.1016/j.agrformet.2022.108856

References of the meta-analysis

Arunrat N, Pumijumnong N, Sereenonchai S, Chareonwong U, Wang C (2020b) Assessment of climate change impact on rice yield and water footprint of large-scale and individual farming in Thailand[J]. Sci Total Environ 726:137864. https://doi.org/10.1016/j.scitotenv.2020.137864

Babel MS, Agarwal A, Swain DK, Herath S (2011b) Evaluation of climate change impacts and adaptation measures for rice cultivation in Northeast Thailand[J]. Clim Res 46(2):137–146. https://doi.org/10.3354/cr00978

Banerjee S, Das S, Mukherjee A, Mukherjee A, Saikia B (2016) Adaptation strategies to combat climate change effect on rice and mustard in Eastern India[J]. Mitig Adapt Strat Gl 21(2):249–261. https://doi.org/10.1007/s11027-014-9595-y

Belder P, Bouman B, Cabangon R, Guoan L, Quilang E, Yuanhua L, Spiertz J, Tuong TP (2004) Effect of water-saving irrigation on rice yield and water use in typical lowland conditions in Asia[J]. Agr Water Manage 65(3):193–210. https://doi.org/10.1016/j.agwat.2003.09.002

Bhuvaneswari K, Geethalakshmi V, Lakshmanan A, Anbhazhagan R, Sekhar DNU (2014) Climate change impact assessment and developing adaptation strategies for rice crop in western zone of Tamil Nadu[J]. J Agrometeorol 16(1):3. https://doi.org/10.54386/jam.v16i1.1484

Boonwichai S, Shrestha S, Babel MS, Weesakul S, Datta A (2019b) Evaluation of climate change impacts and adaptation strategies on rainfed rice production in Songkhram River Basin, Thailand[J]. Sci Total Environ 652:189–201. https://doi.org/10.1016/j.scitotenv.2018.10.201

Cao N, Chen X, He H et al (2017) Effects of different irrigation treatments at tassel and flowering stage on resistance to low temperature, yield and physiological characteristics of late rice[J]. J Appl Ecol 28(12):3935–3944 (in Chinese)

Chun JA, Li S, Wang Q, Lee W, Lee E, Horstmann N, Park H, Veasna T, Vanndy L, Pros K (2016b) Assessing rice productivity and adaptation strategies for Southeast Asia under climate change through multi-scale crop modeling[J]. Agr Syst 143:14–21. https://doi.org/10.1016/j.agsy.2015.12.001

Deb P, Tran DA, Udmale PD (2016b) Assessment of the impacts of climate change and brackish irrigation water on rice productivity and evaluation of adaptation measures in Ca Mau province, Vietnam[J]. Theor Appl Climatol 125(3):641–656. https://doi.org/10.1007/s00704-015-1525-8

Dharmarathna W, Herath S, Weerakoon SB (2014b) Changing the planting date as a climate change adaptation strategy for rice production in Kurunegala district, Sri Lanka[J]. Sustain Sci 9(1):103–111. https://doi.org/10.1007/s11625-012-0192-2

Guo Y, Wu W, Du M, Bryant CR, Li Y, Wang Y, Huang H (2019b) Assessing potential climate change impacts and adaptive measures on rice yields: the case of Zhejiang province in China[J]. Sustainability-Basel 11(8):2372. https://doi.org/10.3390/su11082372

Halder D, Kheroar S, Srivastava RK, Panda RK (2020b) Assessment of future climate variability and potential adaptation strategies on yield of peanut and Kharif rice in eastern India[J]. Theor Appl Climatol 140(3):823–838. https://doi.org/10.1007/s00704-020-03123-5

Horai K, Ishii A, Mae T, Shimono H (2013) Effects of early planting on growth and yield of rice cultivars under a cool climate[J]. Field Crop Res 144:11–18. https://doi.org/10.1016/j.fcr.2012.12.016

Huang M, Fang S, Cao F, Chen J, Shan S, Liu Y, Lei T, Tian A, Tao Z, Zou Y (2020) Early sowing increases grain yield of machine-transplanted late-season rice under single-seed sowing[J]. Field Crop Res 253:107832. https://doi.org/10.1016/j.fcr.2020.107832

Huang H, Xiong W, Lin Z (2012) Climate change impact and adaptation on rice production in Seville: strengthening the scientific and technological foundation for meteorological modernization[C]. The 29th Annual Meeting of the Chinese Meteorological Society, Shenyang, Liaoning, China. (in Chinese)

Islam ARMT, Shen S, Yang S, Hu Z, Rahman MA (2020b) Spatiotemporal rice yield variations and potential agro-adaptation strategies in Bangladesh: a biophysical modeling approach[J]. Sustain Prod Consump 24:121–138. https://doi.org/10.1016/j.spc.2020.07.005

Jalota SK, Vashisht BB (2016b) Adapting cropping systems to future climate change scenario in three agro-climatic zones of Punjab, India[J]. J Agrometeorol 18(1):48. https://doi.org/10.54386/jam.v18i1.899

Jalota SK, Kaur H, Ray SS, Tripathi R, Vashisht BB, Bal SK (2012) Mitigating future climate change effects by shifting planting dates of crops in rice-wheat cropping system[J]. Reg Environ Change 12(4):913–922. https://doi.org/10.1007/s10113-012-0300-y

Jiang M, Shi CL, Liu Y, Jin ZQ (2017) Response of rice production to climate change based on self-adaptation in Fujian province[J]. J Agr Sci-Cambridge 155(5):751–765. https://doi.org/10.1017/S0021859617000016

Jin Z, Ge D, Chen H, Fang J (1995) Effects of climate change on rice production and strategies for adaptation in southern China. Climate Change and Agriculture: Analysis of Potential International Impacts 59:307–323. https://doi.org/10.2134/asaspecpub59.c16

Kim D, Roh J, Kim J, Yun JI (2013a) The influence of shifting planting date on cereal grains production under the projected climate change[J]. Korean J Agric for Meteorol 15(1):26–39. https://doi.org/10.5532/KJAFM.2013.15.1.026

Kim HY, Ko J, Kang S, Tenhunen J (2013b) Impacts of climate change on paddy rice yield in a temperate climate[J]. Global Change Biol 19(2):548–562. https://doi.org/10.1111/gcb.12047

Krishnan P, Swain DK, Bhaskar BC, Nayak SK, Dash RN (2007) Impact of elevated CO_2 and temperature on rice yield and methods of adaptation as evaluated by crop simulation studies[J]. Agr Ecosyst Environ 122(2):233–242. https://doi.org/10.1016/j.agee.2007.01.019

Lakshmanan A, Geethalakshmi V, Rajalakshmi D, Bhuvaneswari K, Srinivasan R, Sridhar G, Sekhar NU, Annamalai H (2011) Climate change adaptation strategies in the Bhavani basin using the SWAT model[J]. Appl Eng Agric 27(6):887–893. https://doi.org/10.13031/2013.40623

Li Y, Wu W, Ge Q, Zhou Y, Xu C (2016) Simulating climate change impacts and adaptive measures for rice cultivation in Hunan province, China[J]. J Appl Meteorol Clim 55(6):1359–1376. https://doi.org/10.1175/JAMC-D-15-0213.1

Li J (2020) Research on adaptation strategy of rice production in Shenyang area to climate change based on ORYZA20000 model[D]. Shenyang Agricultural University. (in Chinese)

Liu C, Wang L, Le Cocq K, Chang C, Li Z, Chen F, Liu Y, Wu L (2020b) Climate change and environmental impacts on and adaptation strategies for production in wheat-rice rotations in southern China[J]. Agr Forest Meteorol 292:108136. https://doi.org/10.1016/j.agrformet.2020.108136

Ma R, Jiang M, Xue CY et al (2016) Response of rice production to future climate change in southern Henan based on adaptive adjustment[J]. China Rice Science 30(04):417–430 (in Chinese)

Ma X (2017) Research on the response and adaptive strategies of rice to climate change in Shenyang region[D]. Shenyang Agricultural University. (in Chinese)

Meng G, Zheng R, Chen H, Ma G, Wei Z, Xiang G, Zhou J (2020) Plant-atmosphere and soil-atmosphere temperature differences and their impact on grain yield of super hybrid rice under different irrigation conditions[J]. PLoS ONE 15(12):e243580. https://doi.org/10.1371/journal.pone.0243580

Nasir IR, Rasul F, Ahmad A, Asghar HN, Hoogenboom G (2020) Climate change impacts and adaptations for fine, coarse, and hybrid rice using CERES-rice[J]. Environ Sci Pollution R 27(9):9454–9464. https://doi.org/10.1007/s11356-019-07080-z

Pan J, Liu Y, Zhong X, Lampayan RM, Singleton GR, Huang N, Liang K, Peng B, Tian K (2017) Grain yield, water productivity and nitrogen use efficiency of rice under different water management and fertilizer-N inputs in South China[J]. Agr Water Manage 184:191–200. https://doi.org/10.1016/j.agwat.2017.01.013

Pei G, Zhang Y, Zhu D et al (2007) Effects of different moisture treatments on growth and yield of late rice[J]. Southwest Journal of Agriculture 12(04):573–576 (in Chinese)

Rajwade YA, Swain DK, Tiwari KN (2018b) Effect of irrigation method on adaptation capacity of rice to climate change in subtropical India[J]. Int J Plant Prod 12(3):203–217

Rao G, Xiao L, Gan H et al (2012) A preliminary study on the optimal sowing period of rice in Guangdong under climate warming[J]. China Agricultural Bulletin 28(05):300–305 (in Chinese)

Sandhu SS, Mahal SS, Vashist KK, Buttar GS, Brar AS, Singh M (2012) Crop and water productivity of bed transplanted rice as influenced by various levels of nitrogen and irrigation in northwest India[J]. Agr Water Manage 104:32–39. https://doi.org/10.1016/j.agwat.2011.11.012

Satapathy SS, Swain DK, Herath S (2014b) Field experiments and simulation to evaluate rice cultivar adaptation to elevated carbon dioxide and temperature in sub-tropical India[J]. Eur J Agron 54:21–33. https://doi.org/10.1016/j.eja.2013.11.010

Satapathy SS, Swain DK, Pasupalak S, Herath S (2019) Nutrients management and planting time adaptation to climate change for wet season rice production in subtropical India[J]. Crop Pasture Sci 70(10):858–867. https://doi.org/10.1071/CP19164

Saxena R, Kumar SN (2014) Simulating the impact of projected climate change on rice (Oryza sativa L.) yield and adaptation strategies in major rice growing regions of India[J]. J Agrometeorol 16(1):18. https://doi.org/10.54386/jam.v16i1.1481

Shrestha S, Trang BTT (2015b) Assessment of the climate-change impacts and evaluation of adaptation measures for paddy productivity in Quang Nam province, Vietnam[J]. Paddy Water Environ 13(3):241–253. https://doi.org/10.1007/s10333-014-0434-2

Shrestha S, Deb P, Bui TTT (2016) Adaptation strategies for rice cultivation under climate change in Central Vietnam[J]. Mitig Adapt Strat Gl 21:15–37. https://doi.org/10.1007/s11027-014-9567-2

Singh P, Swain DK, Bhadoria PBS, Jagadamma S (2019) Effect of planting system and elevated CO_2 environment on soil $NH4^+$–N and NO3$^-$N content and yield of hybrid rice in Subtropical India[J]. Int J Plant Prod 13(2):141–153. https://doi.org/10.1007/s42106-019-00039-7

Sumathi A, Mohandass S, Ramasamy S (2015) Impact of climate change scenario on rice production in two planting methods: a simulation study[J]. Int J Environ Sci Te 12(5):1539–1548. https://doi.org/10.1007/s13762-014-0517-z

Sun Y, Ma J, Sun Y, Xu H, Yang Z, Liu S, Jia X, Zheng H (2012) The effects of different water and nitrogen managements on yield and nitrogen use efficiency in hybrid rice of China[J]. Field Crop Res 127:85–98. https://doi.org/10.1016/j.fcr.2011.11.015

Swain DK (2010) Climate change impact assessment and evaluation of agro-adaptation measures for rice production in Eastern India[J]. J Environ Inform 16(2):94–101. https://doi.org/10.3808/JEI.201000181

Truong AD (2020) Shifting crop planting calendar as a climate change adaptation solution for rice cultivation region in the Long Xuyen Quadrilateral of Vietnam[J]. Chil J Agr Res 80(4):468–477. https://doi.org/10.4067/S0718-58392020000400468

Tu D, Jiang Y, Liu M, Zhang L, Chen L, Cai M, Ling X, Zhan M, Li C, Wang J (2020) Improvement and stabilization of rice production by delaying sowing date in irrigated rice system in central China[J]. J Sci Food Agr 100(2):595–606. https://doi.org/10.1002/jsfa.10053

Wang W, Sun F, Peng S et al (2013) Simulation of rice irrigation water demand in response to climate change[J]. Journal of Agricultural Engineering 29(14):90–98 (in Chinese)

Wang Q, Chun J A, Lee W, Li S, Seng V (2017) Shifting planting dates and fertilizer application rates as climate change adaptation strategies for two rice cultivars in Cambodia[J]. 한국기후변화학회지 8(3):187–199. https://doi.org/10.15531/KSCCR.2017.8.3.187

Xu C, Wu W, Ge Q, Zhou Y, Lin Y, Li Y (2017) Simulating climate change impacts and potential adaptations on rice yields in the Sichuan Basin, China[J]. Mitig Adapt Strat Gl 22(4):565–594. https://doi.org/10.1007/s11027-015-9688-2

Yang X, Tang X, Wen X et al (2014) Effect of sowing period on aroma 2-acetyl-1-pyrroline content and yield in late-season aromatic rice[J]. J Ecol 34(05):1156–1164 (in Chinese)

Yao F, Huang J, Cui K, Nie L, Xiang J, Liu X, Wu W, Chen M, Peng S (2012) Agronomic performance of high-yielding rice variety grown under alternate wetting and drying irrigation[J]. Field Crop Res 126:16–22. https://doi.org/10.1016/j.fcr.2011.09.018

Yu Q (2010) Effect of different irrigation methods on rice yield and water utilization[J]. Guizhou Agricultural Science 38(08):37–39 (in Chinese)

Zhang Y, Tang Q, Zou Y, Li D, Qin J, Yang S, Chen L, Xia B, Peng S (2009) Yield potential and radiation use efficiency of "super" hybrid rice grown under subtropical conditions[J]. Field Crop Res 114(1):91–98. https://doi.org/10.1016/j.fcr.2009.07.008

Zhang S, He Q, Wang H et al (2018) Effect of nitrogen application under controlled irrigation on nitrogen use efficiency and yield of hybrid indica rice F superior 498[J]. Journal of Plant Nutrition and Fertilizer 24(01):82–94 (in Chinese)

Zhang L, Zhang C, Zhang J et al (2019) Assessment of extreme heat loss and adaptation measures for first-season rice in Hunan province based on CERES-rice model[J]. J Ecol 39(17):6293–6303 (in Chinese)

Zhao H (2006) Impact of climate change on rice production in the middle and lower reaches of Yangtze River and its adaptation[D]. Chinese Academy of Agricultural Sciences. (in Chinese)

Zhou T (2018) Research on adaptation of rice production in Fujian province under new emission scenarios[D]. Fujian Agriculture and Forestry University. (in Chinese)