Quantifying the impact of global warming on China's rice production

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Abstract

China is the world's largest producer of rice, so even small changes in China's rice yield can have important consequences for global food security. Climate warming is widely expected to affect rice yields, but results are equivocal and variation in rice cropping systems and climatic conditions between studies complicates country-scale yield assessments. Here we show, through field experiments and analysis of two large-scale, long-term data sets, that yield responses to warming differ strongly and consistently between China's three main rice cropping systems. Whereas warming increases yields in "single rice" systems (+12.1% °C^{-1}), it decreases rice yields in "middle rice" systems (-6.9% °C^{-1}), and has contrasting effects for early (-6.0% °C^{-1}) and late (11.4% °C^{-1}) rice in "double rice" systems. We further show that the contribution of these cropping systems to China's total rice production has shifted dramatically over recent decades. Importantly, the planting area of the cropping system with the strongest negative response to warming (i.e. middle rice) is expanding at the cost of double rice systems. These results suggest that maintaining the current distribution of China's rice cropping systems is essential to ensure global food security in a changing climate.

Keyword: climate change; food security; cropping system

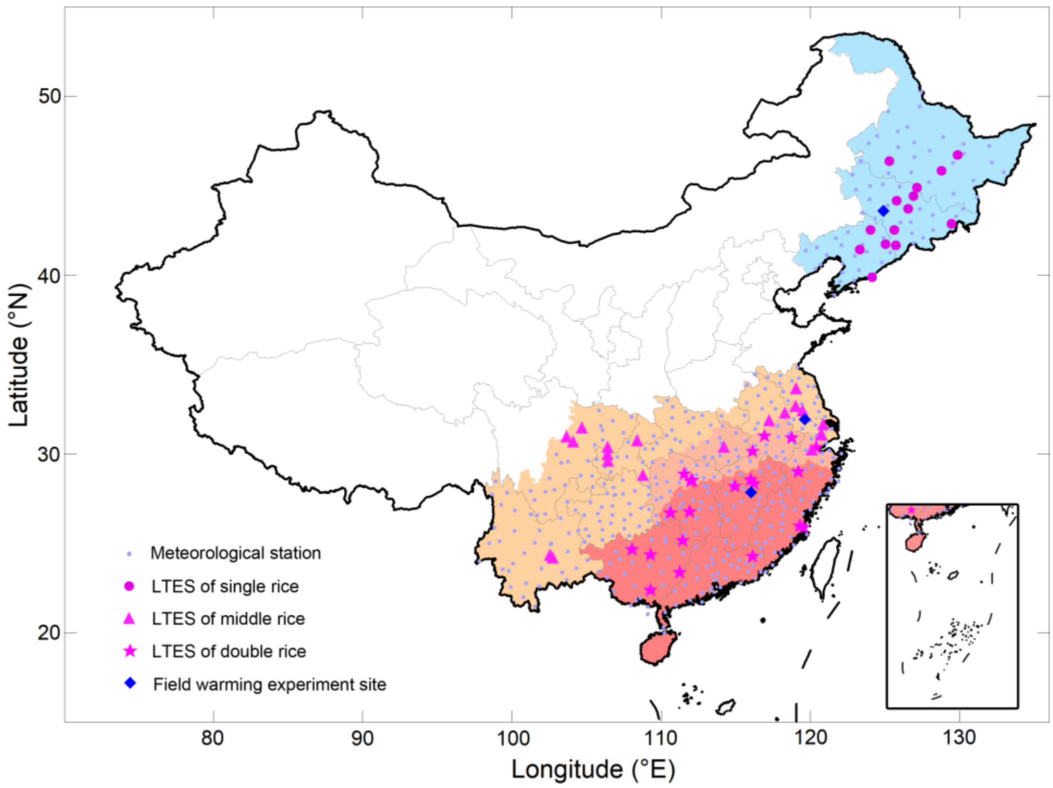
Introduction

With more than half of all people depending on rice as a primary source of caloric intake, rice is the world's most important staple food (Maclean, Dawe, Hardy, & Hettel, 2002). By 2050, global demand for rice is expected to increase by 28% (Alexandratos & Bruinsma, 2012). As the world's largest rice producer, China will play a central role in meeting these demands. China also consumes and imports more rice than any other country (FAOSTAT, 2017), meaning that even small changes in China's rice production will strongly affect the global rice market.

The global mean air temperature is predicted to rise by 1.0–1.7 °C by 2050 (IPCC, 2013). Because temperature plays a key role in crop development and growth (Zhang, Huang, & Yang, 2013, García, Dreccer, Miralles, & Serrago, 2015), future climatic warming is widely expected to affect global rice production (Peng et al., 2004; Lobell, Schlenker, & Justin, 2011; van Groenigen, van Kessel, & Hungate, 2013; Zhao et al., 2017). However, air temperature and precipitation patterns vary strongly across China, suggesting that climatic warming impacts on Chinese rice yields will vary both in space and time (Tao et al., 2013).

Three rice cropping regions cover 96% of China's rice growing area (PINC, 2016), each with its own cropping system and rice type: single rice cropping systems in the Northeast ("single rice"), middle rice cropping systems in East and central China ("middle rice"), and double rice cropping systems in the South ("early rice" and "late rice") (Fig. 1, Supplementary text). Even though these regions have very different climates (Table 1), previous efforts to synthesize rice yield responses to warming did not consider differences between rice cropping systems (Peng et al., 2004; Lobell et al., 2011; van Groenigen et al., 2013; Tao et al., 2013; Challinor, et al., 2014; Zhao et al., 2017).

Here, we present a comprehensive study to quantify warming impacts on Chinese rice production. First, we analyzed two independent long-term data sets of climatic variables and rice yields: one data set of observations from 74 long-term experimental (LTE) stations (Fig. 1), and a data set of province-level aggregated yield data. Both data sets include data from all three cropping regions and cover a period of 24 and 36 years, respectively. Second, we conducted field warming experiments in each of China's main rice cropping regions.



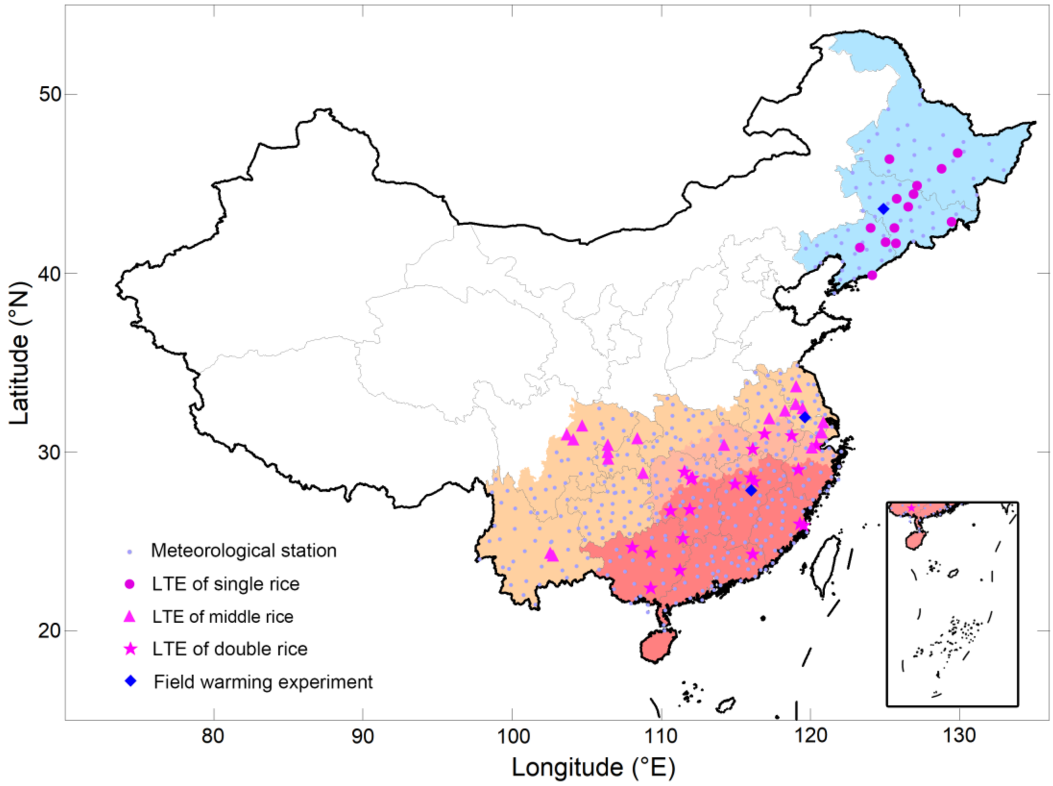


Figure 1 | Map of the major Chinese rice cropping regions, field warming experimental sites and long-term experimental stations for field observations used in this study. The single rice cropping region is indicated in blue, the middle rice cropping region is indicated in light orange, and the double rice cropping region is indicated in light red. LTES: Long-term experimental station.

Material and methods

Long-term field observations (Data set 1)

We collected rice yield data and information on agronomic practices from four networks of LTE stations: 1) the National Monitoring Base of Soil Fertility and Fertilizer Efficiency, Chinese Academy of Agricultural Sciences (1990-2013); 2) the Nutrient Cycling long-term Experiments in the Chinese Ecological Research Network, Chinese Academy of Sciences (1989-2013); 3) the Soil Fertility Management Experiments in China (1980-2013); and 4) the

Agricultural Experiment Stations of the Chinese meteorological administration (CMA) (1990-2013) (Data set 1, Supplementary Table S4). Data set 1 includes 15, 19, and 21 LTE stations in single, middle, and double rice cropping systems, respectively (Fig. 1). Meteorological data (that is, maximum temperature (Tmax), minimum temperature (Tmin), average temperature (Tavg) and precipitation (Prec)) were collected at each station.

Province-level aggregated data (Data set 2)

We identified 3, 10, and 9 provinces or metropolis cities in the single rice, middle rice, and double rice regions, respectively (Supplementary Table S5). Data on total sown rice area and rice production for each rice type in each province or metropolis city from 1980 to 2015 were collected from the Planting Information Network of China (PINC, 2016). From 1993 to 2013, sowing, flowering, and maturity dates for each rice type in each province or metropolis city were collected from agricultural phenological stations of the CMA. There are 72, 104, and 92 agricultural phenological stations in single rice, middle rice, and double rice cropping system area, respectively (Fig. 1). Meteorological data (that is, daily Tmax, Tmin, Tavg, and Prec) were collected from 94, 219, and 83 meteorological stations of CMA in single rice, middle rice, and double rice cropping system area, respectively (Fig. 1).

Field warming experiments

We conducted warming experiments at three sites in China to cover the three major Chinese rice cropping regions, using warming techniques that increased the average air temperatures of crop canopy by 0.5~1.0 °C during the nighttime (19:00–06:00) (Supplementary Fig. S1). At all three sites and for all years, the experiments consisted of three replicate plots for the ambient and warming treatments in a randomized complete block design. The single rice cropping system experiments were conducted during 2007, 2008, 2010, and 2011 in Gongzhuling city (124.9E, 43.6N), Jilin province. The middle rice cropping system experiments occurred in 2008, 2010, and 2011 in Danyang city (119.6E, 32.0N), in Jiangsu province. The double rice cropping system experiments were conducted in 2007, 2010, and 2011 in Jinxian county (116.2E, 28.4N), Jiangxi province.

Air temperatures were increased by passive nighttime warming (PNW) (Beier et al., 2004) from 2007-2010 at all sites. Warming plots were covered at night with reflective curtains to increase air temperatures, because reflective curtains reduce the loss of infrared radiation (Beier et al., 2004). The reflective curtains, which were attached to galvanized steel tubes at both ends, were spread out at sunset (around 19:00) and rolled up at sunrise (around 6:00) by hand. For the single, middle, early, and late rice experiments, PNW was replaced in 2011 with night-time free air temperature increase (FATI), a fully automated system that may minimize effects on the microclimate of the experimental plots (Zhang et al., 2005). Like PNW, the FATI facility switched on at 19:00 and switched off at 6:00 the next day during the entire rice growth period. Climatic conditions, soil properties and management practices at each site are summarized in Table 3; a detailed description of the experimental setup is provided by Chen et al. (2017). All other management practices followed local recommendations.

Data analysis

Long-term field observations (Data set 1)

According to the sowing date and maturity date, we calculated the mean daily Tmax, Tmin, Tavg, and total precipitation for each rice growing season for each LTE station in our dataset.

We then calculated a) the linear trends of rice yield and climate factors over time, and b) the correlation coefficients between climatic factors and rice yields. Briefly, we used a time-series model to assess the impact of warming on rice yield (Lobell, & Burke, 2010). We found no significant temporal trend in rice yields for 83% of the LTE stations (Supplementary Table S4), presumably because the agronomic practices remained similar during the experiment period. Thus, we used actual (that is, not de-trended) rice yields for our analyses:

$$Log(Y_{i,t})=c_t+\alpha\times T_{i,t}+\beta\times P_{i,t}+\varepsilon_{i,t} \quad (1)$$

Where Y is the actual rice yield, i is the LTE and t is the year, T is temperature (°C), P is precipitation (mm), α is the sensitivity coefficients of rice yield to temperature (% °C^{-1}), β is the sensitivity coefficients of rice yield to precipitation (% mm^{-1}), c is the fixed effect and ε is the error term. Because only Tmin significantly correlated with the rice yield in all cropping systems (Table 2), we used mean daily minimum temperature in the model. All analyses were performed in Eviews 6.0.

Province-level data (Data set 2)

Because we only had access to province–level rice yield data, we used the mean value of climatic data of the meteorological stations in the corresponding province. For each meteorological station, we estimated the mean daily Tmax, Tmin and Tavg, and total precipitation during the rice growth period, using the sowing date and maturity date of the nearest agricultural phenological station. The average values of sowing and maturity dates from 1993 to 2013 were considered as the sowing and maturity dates for the 1980-2015 period. Province–averaged rice yields (kg/ha) for each rice type were calculated by dividing rice production data by rice sown area.

Rice yields significantly increased over time in 90% of the provinces (Supplementary Table S5), presumably because of changes in agronomic practices. Thus, we used the de-trended method (Goldblum, 2009; Tao et al., 2014) to eliminate the effects of changes in agronomic practices on rice yield:

$$Ya = d*\text{year}+\beta*X+\varepsilon \qquad (2)$$

$$X = a*\text{Tavg}+b*\text{P} \qquad (3)$$

$$Yt_n = Ya_n - n*d \quad (n=0, \ldots, n-1) \qquad (4)$$

Where Ya is rice yield (kg ha^{-1}), d is time trend coefficient, β is a vector of coefficients and X is a vector of variables (Tavg, P), a ($kg \cdot ha^{-1} \cdot °C^{-1}$) and b ($kg \cdot ha^{-1} \cdot mm^{-1}$) are impact coefficients of mean temperature and precipitation, respectively. Yt_n and Ya_n are the de-trended and actual yields of year n, respectively, using the yield of 1980 as the reference level. Using de-trended yields instead of actual yields, we applied the same approach as for Data set 1 to calculate correlation coefficients between climatic factors and rice yields.

Field warming experiments

Within each experiment, the magnitude of the warming and the responses of rice yield to PNW and FATI were statistically indistinguishable and quantitatively similar (Supplementary Table S3). Thus, we combined results from both techniques to estimate the responses to warming. We conducted a two–way (warming and year) ANOVA to test for significant differences between the warming and the ambient treatments in each cropping system. All analyses were performed with the statistical package SPSS 18.0. Differences were considered significant at $p < 0.05$.

For each cropping system, we calculated the average effect of warming on rice yield

(E, % per °C warming) using the following equation:

$$E = \sum (W_i - C_i)/(C_i \times (Tw_i - Tc_i))/N \quad (5)$$

Where i is the experimental year (e.g. 1,2...n), N is the total number of years, W (kg ha^{-1}) is the mean rice yield with warming, C (kg ha^{-1}) is the mean rice yield in the control treatment, Tw is the mean daily minimum temperature (°C) under warming during the rice growing season, and Tc is the daily mean minimum temperature (°C) under the control during the rice growing season.

Warming impact on rice production

Based on the effects of warming (1.0 °C) on rice yield and rice planted area and rice yield of different rice cropping systems in 2015, we estimated the effects of warming on China's rice production (EP, %):

$$EP = \sum P_j \times \alpha_j / \sum P_j \quad (6)$$

$$P_j = A_j \times Y_j \quad (7)$$

where P is the rice production. α is the impact of increasing minimum temperature on rice yield (% per 1°C), j is the rice type, A is the rice planted are, and Y is the rice yield in 2015. We used the three independent estimates of α_j in Fig.1a-c to calculate EP_a, EP_b, and EP_c, respectively. We then used these values to calculate a mean EP, a long with their standard error.

Results

Warming and rice yield

All three cropping systems have experienced warming from 1980 to 2015 during rice growing seasons (Table 1). In the single rice system, average daily Tmin increased more strongly than average daily Tmax. In the middle rice and double rice systems, maximum temperatures raised more quickly than daily average or minimum temperature.

Table 1 Average values and warming trends of daily mean, maximum and minimum temperatures during rice growing seasons in the major Chinese rice cropping system over 1980-2015.

Rice type	Temperature index	**Tavg**	**Tmax**	**Tmin**
Single rice	Average value (˚C)	18.78 ± 0.54	24.42 ± 0.61	13.57 ± 0.54
	Warming trend (˚C/decade)	0.312**	0.289**	0.355**
Middle rice	Average value (˚C)	23.01 ± 0.43	27.96 ± 0.54	19.32 ± 0.41
	Warming trend (˚C/decade)	0.341**	0.387**	0.318**
Early rice	Average value (˚C)	23.26 ± 0.54	27.66 ± 0.64	19.99 ± 0.49
	Warming trend (˚C/decade)	0.277**	0.293**	0.286**
Late rice	Average value (˚C)	25.98 ± 0.48	30.66 ± 0.55	22.60 ± 0.45
	Warming trend (˚C/decade)	0.248**	0.263**	0.249**

Temperature values are presented as mean ± standard error (n=36). Tavg, daily mean temperature; Tmax, daily maximum temperature; Tmin, daily minimum temperature; * and ** indicate significant warming trends at $p < 0.05$ and 0.01, respectively.

Rice yields in Data set 1 correlated most strongly with daily minimum temperatures (Table 2; Supplementary Fig. S3, S4), suggesting that warming impacts rice yield through its effect on daily minimum temperature (Peng et al., 2004; Welch et al., 2010). Similar results were found in the Data set 2; rice yield correlated with daily minimum temperatures, although the effect was not significant for early rice.

Table 2 Correlation coefficients between climatic factors and rice yields in China.

Data source	**Rice cropping systems**	**Rice type**	**Tavg**		**Tmax**		**Tmin**		**Prec**	
			r	**Sig.**	***r***	**Sig.**	***r***	**Sig.**	***r***	**Sig.**
Long-term field observations (Data set 1)	Single	Single	0.570	*	0.132	NS	0.676	**	-0.061	NS
	Middle	Middle	-0.518	*	-0.618	*	-0.551	*	0.507	*
	Double	Early	-0.284	NS	-0.141	NS	-0.310	*	-0.269	NS
		Late	0.502	*	0.417	NS	0.613	**	-0.368	NS
Province-level aggregated data (Data set 2)	Single	Single	0.425	**	0.289	NS	0.538	**	-0.019	NS
	Middle	Middle	-0.472	**	-0.476	*	-0.401	*	0.253	NS
	Double	Early	-0.043	NS	-0.074	NS	-0.095	NS	-0.191	NS

Late	0.656	**	0.562	**	0.598	**	-0.200	NS

r and Sig. indicate correlation coefficients and significance level; Tavg, daily mean temperature; Tmax, daily maximum temperature; Tmin, daily minimum temperature; Prec, precipitation; * and ** indicate significant warming trends at $p < 0.05$ and $p < 0.01$, respectively. NS; not significant.

To quantify warming effects on rice yield, we plotted variations in yield against variation in average daily minimum temperature for each rice cropping system. Applying this approach to both data sets, we found remarkably consistent results: warming stimulated yield of single rice and late rice, but it suppressed yield of early and middle rice (Fig. 2a, b). Our field warming experiments yielded similar results (Fig. 2c, Supplementary Table S2, and Data set 3). Thus, three independent lines of evidence consistently show that warming significantly affects rice yield, and that warming impacts differ strongly between cropping systems. Averaged across the three approaches, warming increases yields in “single rice” systems by +12.6% °C^{-1}, decreases rice yields in “middle rice” systems by -6.4% °C^{-1}, and has contrasting effects for early (-6.1% °C^{-1}) and late (+ 11.3% °C^{-1}) rice in “double rice” cropping systems. If the present structure of rice cropping systems persists, 1 °C increase effects on rice production will be minimal (95% CI: -4.0%~3.9%).

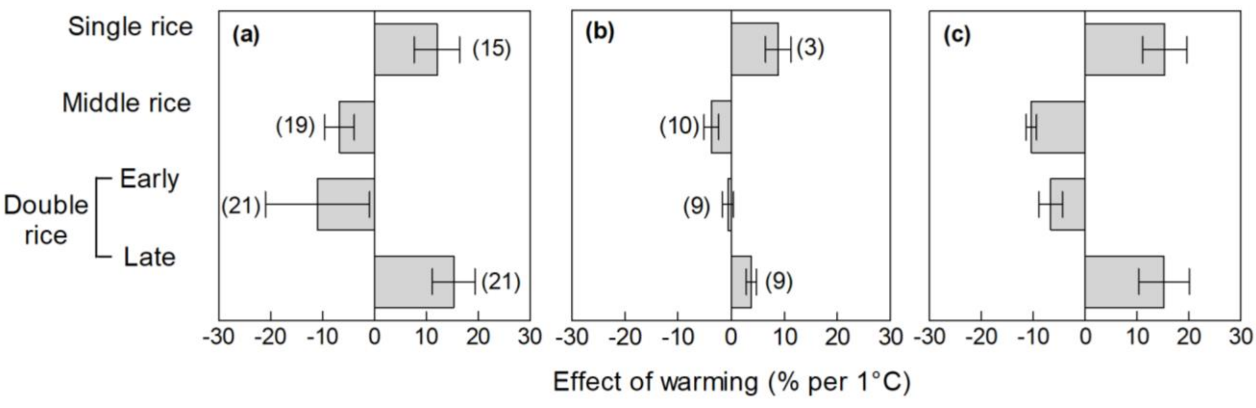


Figure 2 | Warming-induced changes in grain yields of the main Chinese rice cropping systems, as derived from long-term field observations (a), province-level yield data (b) and field warming experiments (c). Data are yield changes (in %) for 1 °C increase in daily minimum temperature ± standard error. Numbers between brackets indicate the number of replicates, that is, the number of experimental stations (a) or provinces (b) for which individual warming effects were derived.

Discussion

Our analyses of both the long-term datasets and our field warming experiments consistently show that the effects of warming on rice yield differed between single rice, middle rice and double rice. Why do yield responses to warming differ between cropping systems? Rice growth and development are highly sensitive to temperature, especially during the reproductive period (Satake & Yoshida, 1978; Estrella, Sparks, & Menzel, 2007; Tao et al., 2013; Espe et al., 2017). For rice yield formation, the optimal temperature is approximately 25-30°C; higher temperatures reduce rice yield through inducing spikelet sterility, whereas lower temperatures slow down pollen development and grain filling (Matsui, Namuco, Ziska, & Horie, 1997; Kim et al., 2011; Giorno, Wolters-Arts, Mariani, & Rieu, 2013). Under current climatic conditions, air temperatures during the reproductive periods of early and middle rice are similar to or exceed optimal temperatures, while temperatures are substantially lower than the optimal in late and single rice seasons (Supplementary Table S1). Thus, whereas climate warming will make temperatures less favorable for early and middle rice, temperatures will become more favorable for late and single rice.

Because warming effects differ strongly between rice cropping systems, estimates of future warming impacts on China's total rice production need to account for the contribution of each system to overall rice production. Indeed, the structure of China's cropping systems has changed substantially over time (Fig. 3a; Supplementary Text). From 1980 to 2015, the area of double rice cropping system shrunk by nearly 50%, while the area of middle rice cropping system increased by a third, and the area of single rice cropping system nearly tripled (Fig. 3a). These changes were mostly due to double rice cropping systems being converted to middle rice cropping systems, combined with an overall decrease in the total area of rice paddy fields.

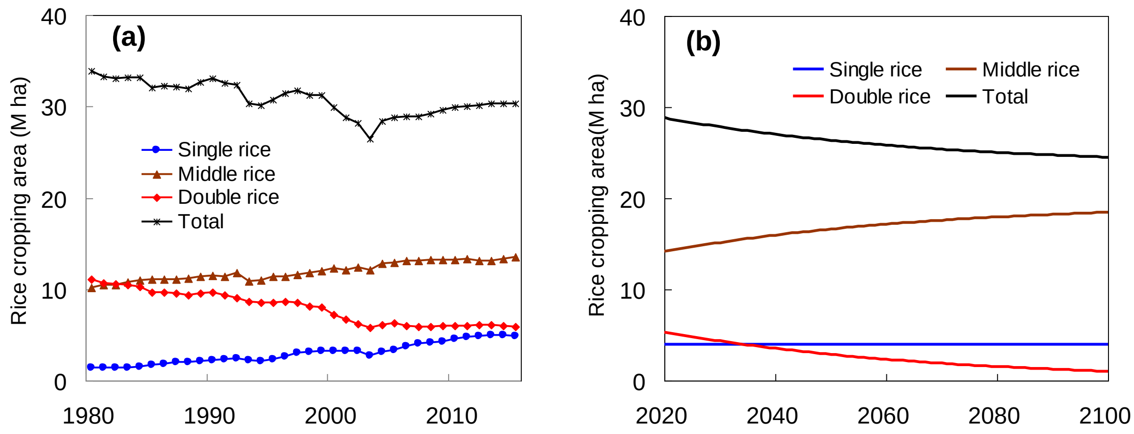


Figure 3 | Changes in the area of each rice cropping system over 1980-2015 (a) and predicted area of each cropping system and total rice sown area (b). Data of the planting area of each rice type were collected from the National Data, China (http://data.stats.gov.cn/easyquery.htm?cn=C01, National Bureau of Statistics of China, 2017). For our extrapolation, we fitted the exponential function e^{ax} to the changes in double rice cropping area between 1980 and 2015. The regression equation of early rice (EA) and late rice (LA) are described by $EAi=11.214e^{-0.0216x}$ ($r^2 = 0.93$, $p< 0.01$) and $LAi=11.537e^{-0.0198x}$ ($r^2 = 0.91$, $p < 0.01$), respectively. We extrapolated the double rice area using these equations. Because recent government regulations stipulate that rice farmers cannot convert their paddies to other forms of land use (Supplementary Text), we assumed that the decreased double rice area will be converted to middle rice.

Because of rural social-economic development, we estimated that shifts in different cropping systems over the last few decades will continue. Extrapolating the changes in the sown areas of double rice systems over the last 36 years, we estimate that the area of double rice cropping system will decrease by approximately 83% in 2100 relative to that of 2015 (Fig. 3b) and that this area will be converted to middle rice. Because land availability and water resource are limited in the single rice cropping region (Liu, Wang, & Gao, 2005), we estimate that the single rice cropping area will remain fixed at 4 M ha.

Because middle rice responds more negatively to warming than either early rice or late rice, the ongoing conversion of double rice cropping systems to middle rice cropping systems will increase the negative warming impact on China's rice production. In fact, average daily minimum temperatures in the current double rice cropping region are higher than in the current middle rice cropping region (Table 1), suggesting that the negative warming effects on future middle rice might be even stronger than our estimates. In addition, converting double rice cropping systems to middle rice systems effectively decreases China's total rice cropping area (Fig. 2b), because paddies that used to be cropped twice per year are now only cropped once. On the other hand, our estimates of *EP* suggest that for the current structure of rice cropping systems, 1°C warming would not substantially affect total rice production in China, as yield losses for early rice and middle rice compensate yield increases for single rice and late rice. Thus, our results suggest that maintaining the current distribution of China's rice cropping systems is essential to ensure global food security in a changing climate.

Two limitations of our study must be noted. First, our estimates of yield responses to warming are based on relatively small changes in temperature; our datasets cover a temperature range of less than 1.5 °C, and our field warming experiments applied warming of 0.5-1°C. Yet, the predicted increase in the temperature for 2050-2100 exceeds 2.0 °C (IPCC, 2013), and negative effects of warming on rice yield are more severe at high temperatures (van Groenigen et al., 2013). Similarly, positive warming effects for single rice and late rice might decrease when average temperatures move closer to the optimum. Second, our analysis considered only the direct effects of warming on yield, but indirect effects of warming can amplify stress, further suppressing rice yield, for example through increased pests and disease

(Piao et al., 2010; Barford, 2013). Droughts and heatwaves are also more likely to occur with rising temperatures, and both will negatively affect crop yields even further (Meehl & Tebaldi, 2004; Sun et al., 2014).

Our results suggest that global warming and shifts in rice cropping systems may interact to reduce China's rice production, and highlight the importance of double rice cropping systems to bolster food security in a warmer climate, as these systems are less susceptible to warming-induced yield losses than middle rice and produce two yields per year. Thus, to prevent large-scale reductions in rice production, double rice cropping systems should be promoted. We propose that future research efforts should focus on technological innovations for multiple rice cropping systems. For instance, new and simplified mechanical rice planting techniques may help to reduce production input and save labor force demand (Farooq, 2011), making double rice cropping systems more attractive to farmers. In addition, several other agronomic strategies may also help to mitigate negative effects of warming on rice production. First, rice sowing dates may be optimized to mitigate high temperature stresses during the reproductive period (Hu, Huang, Sun, & Yu, 2017). Second, ratoon rice planting (i.e., growing a second rice crop from the stubble left behind after the main-crop harvest) may also boost rice production (Harrell, Bond, & Blanche, 2009); farmers can plant once using direct-seeding and harvest twice, which can greatly reduce labor cost and increase farmers' income. Third, new rice cultivar breeding programs may help to enhance rice quality and resistance to abiotic and biotic stresses (Zhang, 2007), and to deal with high temperature stress during the reproductive period (Hu et al., 2017). As the world's largest rice producer, China faces the difficult challenge of securing the global rice supply while our climate continues to change.

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