

Shifts in the extent and location of rice cropping areas match the climate change pattern in China during 1980–2010

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Abstract Knowledge of cropping areas and climate change is crucial to understanding the causes and consequences of global land use change, and the response of rice areas to climate change is a hot topic to global food security. This study investigates the impacts of climate change on suitable areas for rice cultivation and how the actual cultivated area of rice has been altered in response to climate change during the past three decades. To understand whether the shifts in the extent and location of rice cropping areas match the pattern of climate change, the yearly climate data from 726 weather stations and the rice census data from 2,343 counties were employed to simulate the climatically suitable region for rice using the MaxEnt species distribution model, as well as to model the actual geographical distribution of rice using the spatial allocation production model in each decade. The results show that approximately 3.9 % of all Chinese land area (roughly 3.7×10^7 ha) has become suitable for rice due to climate change over the past three decades, representing new potential areas for rice cultivation. Meanwhile, the actual

rice cropping area has increased by approximately 18.2 %, indicating that the extent and location of the rice expansion match the pattern of climate change. However, some spatial inconsistencies did exist between the actual rice area's expansion and the climatically suitable region after 1990. Nevertheless, climate change was a possible factor impacting the geospatial and temporal changes of the actual rice cropping area in China.

Keywords Climate change pattern · Rice suitability area · Actual rice cropping area · China

Introduction

The impacts of global climate change on food systems are expected to be widespread, complex and geographically and temporally variable. Climate change will have many effects on both the supply and demand of food in global food systems (Wheeler and von Braun 2013). Previous work has assessed the security of food systems under climate change using historical statistical studies of the impacts of climate trends and anomalies on food systems (Lobell et al. 2011a), as well as integrated assessment models that link climate change and crop models to assess climate change's impacts on food security such as in China using the CERES crop models and the IPCC SRES A2 and B2 scenarios including CO₂ fertilization effect (Ye et al. 2013). Cropping area change is an important part of land use pattern, and knowledge of the influence of climate change on cropping area is crucial to understanding the causes and consequences of land use change (van Asselen and Verburg 2013).

The change of the rice cropping pattern in response to climate change is of increasing concern to food security

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studies (Brown and Funk 2008). Rice is among the most important food crops in China and represents one of the three major cereals in the country's food system, making it a crucial part of food security in China (Wu et al. 2013). Many studies have reported that climate warming has significant impacts on rice phenology (Tao et al. 2006; Zhang et al. 2013), and yield and production (Peng et al. 2004; Xiong et al. 2013), as determined using statistical analysis (Lobell and Field 2007) and the process-based crop model such as Argo-C model (Yu et al. 2012). However, the response of rice cropping area and climate change, as well as how this influences agricultural land use, is poorly understood (Dale 1997; Veldkamp and Lambin 2001).

Climate change has had two major impacts on the rice cropping area. First, climate variation has changed growing conditions in the existing rice cropping areas, altering the suitable extent for rice cropping (Zhang et al. 2014). Second, climate warming has moved the northern limit of rice cropping and expanded the potential area for rice (Shi et al. 2014). Previous studies have reported that climate warming affects rice cropping systems by extending the northern limits of production: the northern limit of double-cropping rice cultivation has moved northwards (Duan and Zhou 2013), and the northern limit of single-cropping rice has moved from 47°N to 52°N in Northeast China (Piao et al. 2010). Crop suitability zoning focuses on climatic classifications (Yang et al. 2011), which are often linked to crop agro-ecological zoning (FAO 1996) or the species distribution model (Phillips and Dudik 2008), and are also used to evaluate the impacts of climate change on the suitable areas for rice (Duan and Zhou 2013). Previous work has examined the spatial shifts of the potential rice area, indicating that it is possible to cultivate rice in formerly inhospitable environments (Ohta and Kimura 2007). However, only a few studies have considered how the potential area changed due to climate warming, but not actual rice area changes (Gao and Liu 2011).

The change in actual rice cropping area as an element of land use change has been extensively studied at scales ranging from the local to the global (Foley et al. 2005; Verburg et al. 2010). Current knowledge of rice cropping area change is often derived from remote sensing (Xiao et al. 2006), administrative unit censuses (Lin and Ho 2003) and crop production allocation models (Monfreda et al. 2008; Biradar et al. 2009; You and Wood 2006); these studies are often more concerned with spatial and temporal variations. Few land use/land cover models consider climate variables in their predictions (Verburg et al. 2013). A small number of studies have predicted the future land use and land cover under different climate scenarios, but climate change in these studies was considered as a given condition, not a driving force (Yan et al. 2013). The actual

geographical variations of climate change on rice cropping area have been relatively unexplored (Vermeulen et al. 2012).

The causal relationship between climate change and rice cropping area change has therefore been considered only conceptually (Dale 1997; Gao and Liu 2011), and the historical changes of potential and actual rice cropping areas are often analyzed separately, leading to less understanding of the relationship between climate change and rice area change (Mendelsohn and Dinar 2009). The present study combines two datasets on rice area (SPAM and MaxEnt) to quantify the impact of climate change on rice cropping area. By removing other spatial and temporal effects, the present work bridges the gap between the changes in the climatically suitable rice cropping area and those of the actual rice cropping area.

This study investigates the hypothesis that when climate change alters the distribution of the suitable area for rice, actual rice cultivation area will increase in the newly suitable region. To test this hypothesis, the present research integrated the MaxEnt and SPAM models to quantify the impacts of climate change on rice area. The objectives of this study were to analyze (1) the spatial and temporal changes in the potential rice area due to climate change over the past three decades and (2) the spatial and temporal changes in the actual rice cropping area in response to climate change. As a whole, the study aimed to answer whether the extent and location of the actual rice cropping area have been altered due to climate change in China.

Materials and methods

Climate and rice data

To estimate the actual rice cropping area, statistic data for rice area were gathered for use in the SPAM model from provincial and county level sources of the Ministry of Agriculture, China, encompassing 27 provinces and 2,343 counties from 1980 to 2010 (MOA 2011). For estimating the potential rice cropping area, rice species distribution was modeled using the MaxEnt model (Phillips et al. 2009) with rice occurrence samples and climate data as species occurrence data and environmental predictors, respectively. A random sampling was applied to select 302 rice distribution samples from cropland type of the National Land Cover Dataset (Liu et al. 2005). These samples covered major Chinese rice planting areas where rice was planted during the stage of 1980–2005. About 80 % of the 302 samples were used as training data for the simulation, and the remaining 20 % were used as validation data for the simulation model.

The meteorological data were derived from the Chinese Meteorological Data Sharing Network (China Meteorological Data Sharing Service System, CMDSSS, <http://cdc.cma.gov.cn/>) and consisted of the daily and monthly temperatures and rainfall data for 726 sites from 1971 to 2010. Four climatic variables that are closely related to rice growth conditions were used in the MaxEnt model (Duan and Zhou 2011), including continuous days of 18 °C (D_{18}), which reflects the high temperatures that rice requires between heading and flowering; growing season days of rice ($GDD_{10,30}$), which reflects the thermal resources that rice can utilize during the growing period when the temperature is between 10 and 30 °C; mean annual precipitation (P), which reflects the water conditions used as the dividing line among crops and potential evapotranspiration-to-precipitation ratio (PER), which reflects the water balance and the wetness of the climate. D_{18} was derived using the beginning and ending dates of the limit temperature from the meteorological stations, as calculated using the 5 days moving average method; PER and $GDD_{10,30}$ were calculated as follows:

According to the Holdridge life zone system method, PER was calculated by Eq. (1) (Holdridge 1967):

$$PER = \frac{P}{PET} = \frac{P}{58.93 \times BT}, \quad BT = \frac{\sum t}{365} \quad (1)$$

PER is based on the relations between ‘biotemperature’ (BT), mean total annual precipitation (P) and potential evapotranspiration (PET) ratio, where t is the mean of the annual temperature between 0° and 30 °C. And according to previous studies (Lobell et al. 2011b; Wang et al. 2014), $GDD_{10,30}$ is calculated by Eq. (2):

$$GDD_{base,opt} = \sum_{i=1}^N DD_i \quad (2)$$

$$DD = \begin{cases} 0 & \text{if } T_i < T_{base} \\ T - T_{base} & \text{if } T_{base} \leq T_i < T_{opt} \\ T_{opt} - T_{base} & \text{if } T_i > T_{opt} \end{cases}$$

where i is an individual time step (day); T_i is daily average temperature of T_{min} and T_{max} during this time step; T_{base} and T_{opt} are the upper and lower limits of a given temperature range, respectively; DD represents daily growing degree-days; N is the number of days within a certain growing stage. The ranges of normal and extreme temperatures were defined for $T_{base} = 10$ °C and $T_{opt} = 30$ °C for the growth stage of rice in China. The starting growth stage and ending growth stage were simplified as 1st May to 30th September for single-cropping rice-growing season and 1st April to 30th October for double-cropping rice-growing season.

In order to eliminate the effects of climate anomalies, the climate trend data used in the MaxEnt model were representative of the 10 year averages of 1971–1980,

1981–1990, 1991–2000 and 2001–2010. Spatial distribution was calculated using the inverse distance weighting method (IDW), and the spatial resolution was $5' \times 5'$.

Climatically suitable region for rice cropping

The MaxEnt model (version 3.3, <http://www.cs.princeton.edu/~schapire/MaxEnt/>) was employed to simulate the climatically suitable region for rice (CSRR) over the past three decades. The model was developed by Phillips and Dudik (2008) for simulation of the distribution of plant species. The software uses the principle of maximum entropy to infer, without bias, plant species distribution based on limited information on the distribution of unknown plant species (Duan and Zhou 2013). The model considers that in the absence of external forces, an entity always tends to a maximum within applied constraints. Under known conditions, the entities with maximum entropy area are close to the real state. The model selects the optimal distribution from a qualified distribution, and more details of the method are described in Phillips et al. (2006) and Phillips and Dudik (2008).

The MaxEnt model use receiver operating characteristic curves (ROC) to evaluate the accuracy and area contained under the curve (AUC) to measure the quality of a ranking of sites. The AUC is the probability that a randomly chosen presence site will be ranked above a randomly chosen absence site. A random ranking has on average an AUC of 0.5, and a perfect ranking achieves the best possible AUC of 1.0. Models with values above 0.75 are considered potentially useful (Elith 2002; Phillips and Dudik 2008). The ROC curve is obtained by plotting sensitivity on the y-axis and the false-positive rate (1-specificity) on the x axis for all possible thresholds. The AUC standards for the model check are as follows: 0.50–0.60 (failure); 0.60–0.70 (poor); 0.70–0.80 (fair); 0.80–0.90 (good); 0.90–1.0 (excellent).

The climatically suitable region of rice (CSRR) emerges from the relationship of climate variables and the rice species geographical distribution. The MaxEnt model was predicted an appearance frequency (p) of rice in an area with the range of 0–1, which is the reference from the possibility of assessment division reported by the Intergovernmental panel on climate change (IPCC) (Phillips et al. 2006). The climatic suitability of an area for rice cultivation and their respective appearance frequencies were divided as follows: climatically unsuitable region (UR): $p < 0.05$; low climatically suitable region (LSR): $0.05 < p < 0.33$; moderate climatically suitable region (MSR): $0.33 < p < 0.66$; high climatically suitable region (HSR): $p \geq 0.66$. An appearance frequency of $p \geq 0.05$ was considered to be the total climatically suitable class for rice cultivation (Duan and Zhou 2013).

To investigate the sensitivity of rice areas to climate change, cartographic overlay analysis was used to detect CSRR changes from 1980 to 2010. In this analysis, positive climate-sensitive region (PCSR) and negative climate-sensitive region (NCSR) were reclassified to indicate that climate change impact on potential rice area has increase or decrease trend. PCSR is the region of low suitability shift to high suitability which contains UR upgraded to LSR, LSR to MSR and MSR to HSR, while NCSR is the region of high suitability downgraded to low suitability which contains LSR downgraded to UR, MSR to LSR and HSR to MSR.

Change analysis of rice cropping

The spatial distribution of actual rice cropping area was simulated by the SPAM model from 1980 to 2010 at every 10 years with a spatial resolution of $5' \times 5'$. The SPAM model has been employed to explore crop distribution, and previous researchers have applied the model to long-term, large-scale spatial crop distribution in China (Liu et al. 2013). The core of the SPAM-China model consists of two parts: the information entropy distribution probability model and the crop allocation optimization model. For the specific formulas of these models, please refer to You et al. (2009).

To analyze the temporal and spatial variation of the actual rice cultivation area, the spatial distributions of this area between 1980 and 2010 were compared to obtain the spatial changes over the past 30 years. Rice area in the pixel with variation $>5\%$ was considered to be changed. Then, the temporal dynamic characteristics were studied for the three periods during 1980–2010 and reclassified into decreased regions and increased regions.

Analysis of rice area response to climate change

To analyze changes of historical cultivated rice area in the changed CSRR, the spatio-temporal actual and potential rice area were overlaid between 1980 and 2010, along with representative agricultural management practices. It was assumed that if climate change altered the CSRR, then the actual rice area would be increased in the PCSR, otherwise decreased in the NCSR. For example, if climate change caused a UR to change to an LSR from 1980 to 2010, the actual rice sown area would greatly increase in this region over the same period.

Results

Accuracy assessment of the MaxEnt and SPAM models

Using the four climate variables and the rice species samples data, MaxEnt modeled the potential rice area

distribution, and the results in Table 1 indicate that four variables effectively reveal the contribution of climate to the potential distribution of rice where a percentage of over 85 % is generally considered as a dominant impact. The accuracies of the AUCs were 0.912, 0.918, 0.911 and 0.918 in 1971–1980, 1981–1990, 1991–2000 and 2001–2010, respectively, indicating that the climatic variables used in the model provide excellent results for the simulation of the potential rice geographical distribution (Table 1).

The accuracy test for the actual rice area estimated by SPAM is described by Liu et al. (2013). To test the accuracy of SPAM-China for rice area allocation, the present study used MIRCA-2000 (Portmann et al. 2010) and NLCD-1980 (Liu et al. 2005). To ensure the comparability of the data, samples were collected randomly nationwide. Generally, the accuracy assessment showed that SPAM's output reflected the historical spatial and temporal patterns of rice distribution in China (Liu et al. 2013).

The spatial–temporal changes of CSRR

As the appearance frequencies (p) of rice modeled by MaxEnt model, the CSRR classes were divided and shown in Fig. 1. Excluding northern Heilongjiang, the Inner Mongolia Plateau, the Qinghai-Tibet Plateau, northern Gansu and Xinjiang, which have relatively lower thermal requirements for rice, rice can be planted across the major

Table 1 Accuracy assessment of the Maxent model

Period	Climate variables	Contribution percentage (%)	Accumulative contribution percentage (%)	AUC
1971–1980	D_{18} (day)	38.2	38.2	0.912
	P (mm)	29	67.2	
	$GDD_{10,30}$ ($^{\circ}C \cdot day$)	17.8	85.0	
	PER	15.1	100	
1981–1990	P (mm)	36.7	36.7	0.918
	$GDD_{10,30}$ ($^{\circ}C \cdot day$)	33.9	70.6	
	D_{18} (day)	16.3	86.9	
	PER	13.1	100	
1991–2000	D_{18} (day)	42.9	42.9	0.916
	P (mm)	31.7	74.6	
	$GDD_{10,30}$ ($^{\circ}C \cdot day$)	13.9	88.5	
	PER	11.4	99.9	
2001–2010	P (mm)	29.8	29.8	0.918
	D_{18} (day)	28.2	58	
	$GDD_{10,30}$ ($^{\circ}C \cdot day$)	22	80	
	PER	19.9	99.9	

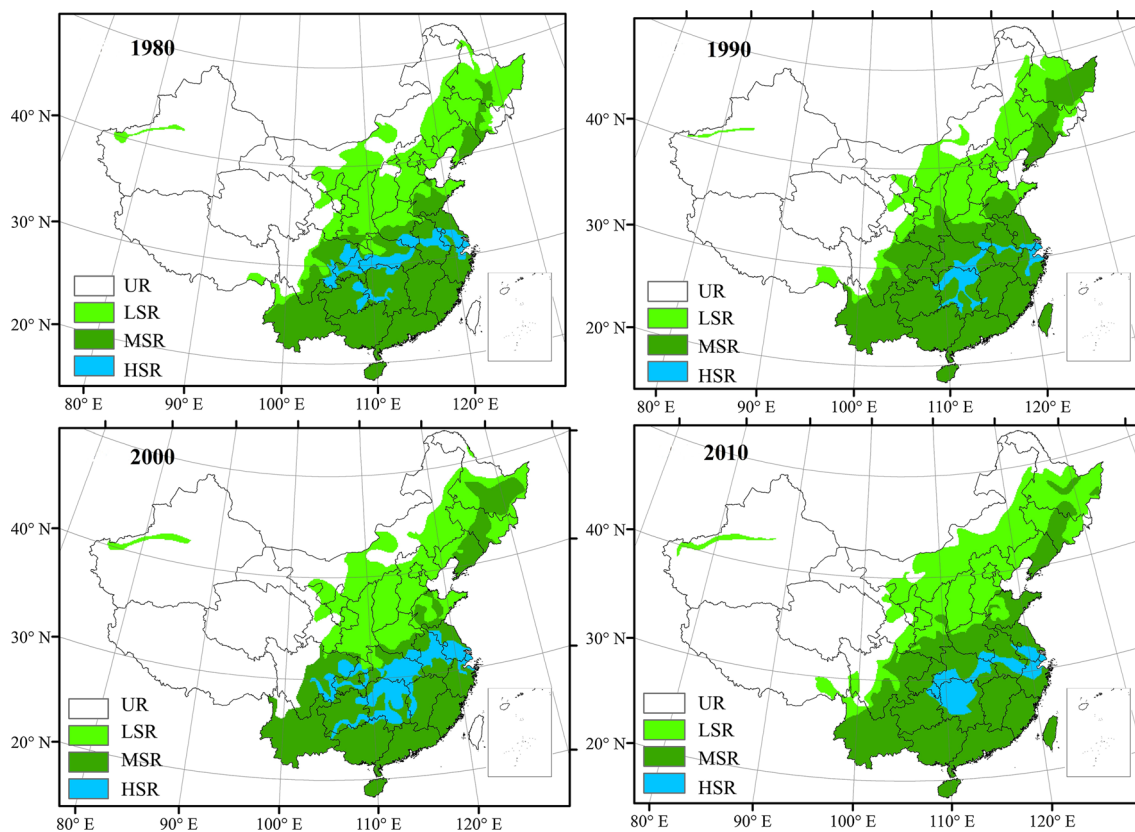


Fig. 1 Spatial distribution of the climatically suitable region for rice in China from 1980 to 2010

part of China. The proportion of UR areas decreased from 52.9 % in 1980 to 49 % in 2010 (Table 2). The suitable region for rice (consisting of LSR, MSR and HSR) increased from 47.1 % in 1980 to 51 % in 2010, primarily due to the northward movement of the northern limits of the CSRR from 48°N in 1980 to 50°N in 2010. LSR areas covered approximately 20 % of China in 1980, mainly distributed in the northern region, ranging from the Heihe watershed, Inner Mongolia plateau, and central Ningxia and southern Shaanxi to northwestern Yunnan. The proportion of LSR decreased to 16.7 % by 1990 because of its conversion to MSR in northeastern China, but recovered to 19.1 % by 2000 and to 20.9 % by 2010. MSR areas covered 23.4 % of the country in 1980; these regions included most of the rice double-cropping areas in China and the single-cropping areas in northeastern China, which is the country's main rice production area. The proportion of MSR increased to 29 % in 1990 but decreased 26.6 % by 2010. HSR areas covered only parts of the double-cropping areas in the Yangtze River Basin, including Hubei, Hunan, Jiangxi, Anhui, Jiangsu and Zhejiang, encompassing approximately 3.6 % of China in 1980, 2.1 % in 1990, 5.6 % in 2000 and 3.4 % in 2010. Overall, two obvious changes in CSRR have occurred due to climate warming: first, the northern limits of rice have moved northwards from 48°N to 50°N, which has enlarged the area of LSR;

second, the MSR area has been enlarged by climate warming, with its northern limits now reaching to the northeast of the Sanjiang Plain (Table 2).

The geographical distributions are shown in Fig. 3a. The climatically sensitive areas covered 11.5, 11.6, 14.1 and 13.0 % of all land area in China in 1980–1990, 1990–2000, 2000–2010 and 1980–2010 respectively (Table 3). PCSR areas are mainly located in northeastern Heilongjiang, central Jilin and Liaoning, northern Shanxi, southern Shaanxi, the edge of the Sichuan basin, northwestern Yunnan and Hunan; together, the climate-sensitive areas of these regions account for 7.4 % of Chinese land area from 1980 to 1990, 6.6 % from 1990 to 2000 and 7.9 % from 2000 to 2010. These areas experienced UR changes to LSR and LSR changes to MSR. NCSR areas are mainly distributed in the 50°N portions of Heilongjiang, southern Jiangsu, central Anhui, eastern Guizhou, Sichuan and Chongqing; the climate-sensitive areas of these regions account for 4.1–6.1 % of Chinese land area from 1980 to 2010 and experienced LSR changes to UR.

The spatial–temporal changes of rice area

The distributions of actual rice area in the four stages simulated by SPAM are shown in Fig. 2. In the spatially changed rice area modeled by SPAM between 1980 and

Table 2 Changes in the frequency of suitability classes for rice from 1980 to 2010

CSRR	1980		1990		2000		2010	
	Pixel number	Percentage (%)	Pixel number	Percentage (%)	Pixel number	Percentage (%)	Pixel number	Percentage (%)
UR	49982	52.9	49117	52.0	49274	52.2	46307	49.0
LSR	18911	20.0	18019	19.1	15797	16.7	19784	20.9
MSR	22137	23.4	21994	23.3	27397	29.0	25165	26.6
HSR	3427	3.6	5327	5.6	1989	2.1	3201	3.4

CSRR climatically suitable region of rice, UR climatically unsuitable region, LSR low climatically suitable region, MSR moderate climatically suitable region, HSR high climatically suitable region

Table 3 Changes in the frequency of positive and negative climate-sensitive regions from 1980 to 2010

CSRR	1980–1990		1990–2000		2000–2010		1980–2010	
	Pixel number	Percentage (%)	Pixel number	Percentage (%)	Pixel number	Percentage (%)	Pixel number	Percentage (%)
PCSR	6969	7.4	6249	6.6	7486	7.9	9277	9.8
NCSR	3873	4.1	4755	5.0	5786	6.1	3043	3.2
CSR	10842	11.5	11004	11.6	13272	14.1	12320	13.0

CSRR climatically suitable region of rice, PCSR positive climate-sensitive regions, NCSR negative climate-sensitive region, CSR climate-sensitive region

2010, rice area increases accounted for 44.5 % of the changed pixels, most of which were located in the single-cropping rice systems of northeast China. Area reductions accounted for 55.5 % of the changed pixels, most of which were located in the double-cropping rice systems of southern China. Taken together, these spatial changes indicate that rice planting in China has decreased over the study period (Fig. 3b). As a proportion of the geospatially changed rice areas, those with increased rice planting accounted for 23.5 % of the total, mainly located in Heilongjiang, Jilin and Shandong over the four periods. The unstable region accounted for 29.5 % of the total, mainly in Sichuan, Hubei, Anhui and Jiangsu—all traditional crop rotation areas in which crops can be easily replaced. The recovered region accounted for 18.67 %, mainly in the double-cropping rice areas of Jiangxi and Hunan, which may have been impacted by labor and rice price when double cropping changed to single cropping. The area with decreased rice planting accounted for 28.36 %, mainly in the rapidly urbanizing areas of Zhejiang, Fujian and Guangdong, where rice cropland has been altered to other utilizations such as urban or industrial land.

In terms of temporal change, rice area decreases occurred in the northwest region of Gansu and Xinjiang during 1980–1990, in the main southern double-cropping system area of Hunan, Jiangxi and Sichuan during 1990–2000 and in the coastal provinces of Guangdong, Fujian, Zhejiang, Shanghai and southern Jiangsu, as well as Beijing, Tianjin and Liaoning, during 2000–2010. Rice area increases were scattered across parts of southern

Hubei, Anhui and central and northeast China during 1980–1990; the Songnen Plain and the Sanjiang Plain in Heilongjiang, north Jiangsu, the Sichuan Basin and north Hainan during 1990–2000; and in the Songnen Plain in Heilongjiang and Jilin, north Jiangsu and north Ningxia during 2000–2010.

The response of actual rice area to CSRR changes

As seen in the spatiotemporal changes of rice area and the climatically suitable region of rice in 1980–2010, a geospatial change in actual rice area was observed in the changed CSRR, which indicates a possible impact of climate change on rice area. As shown in Fig. 3c, both single-cropping and double-cropping rice systems are spatially heterogeneous, and most of the rice area increases occurred in the northern single-cropping systems. Climate suitability increased in this region, and it accounted for 50.1 % of the increase in rice area contained 18.2 % in PCSR and 31.9 % in stable LSR. In the spatial overlay of the climatically suitable and actually cultivated area pixels, approximately 18.2 % of the pixels in the increased cultivated area were located in regions where the climate had become more suitable, indicating that these regions may have benefitted from climate change. Conversely, in southern China, most of the decrease in rice area was located in the stable moderately suitable region, which is also the double-cropping rice region, accounting for 72.3 % of the decrease in cultivation contained 64.5 % decrease in stable MSR and 7.8 % decrease in stable HSR (Table 4).

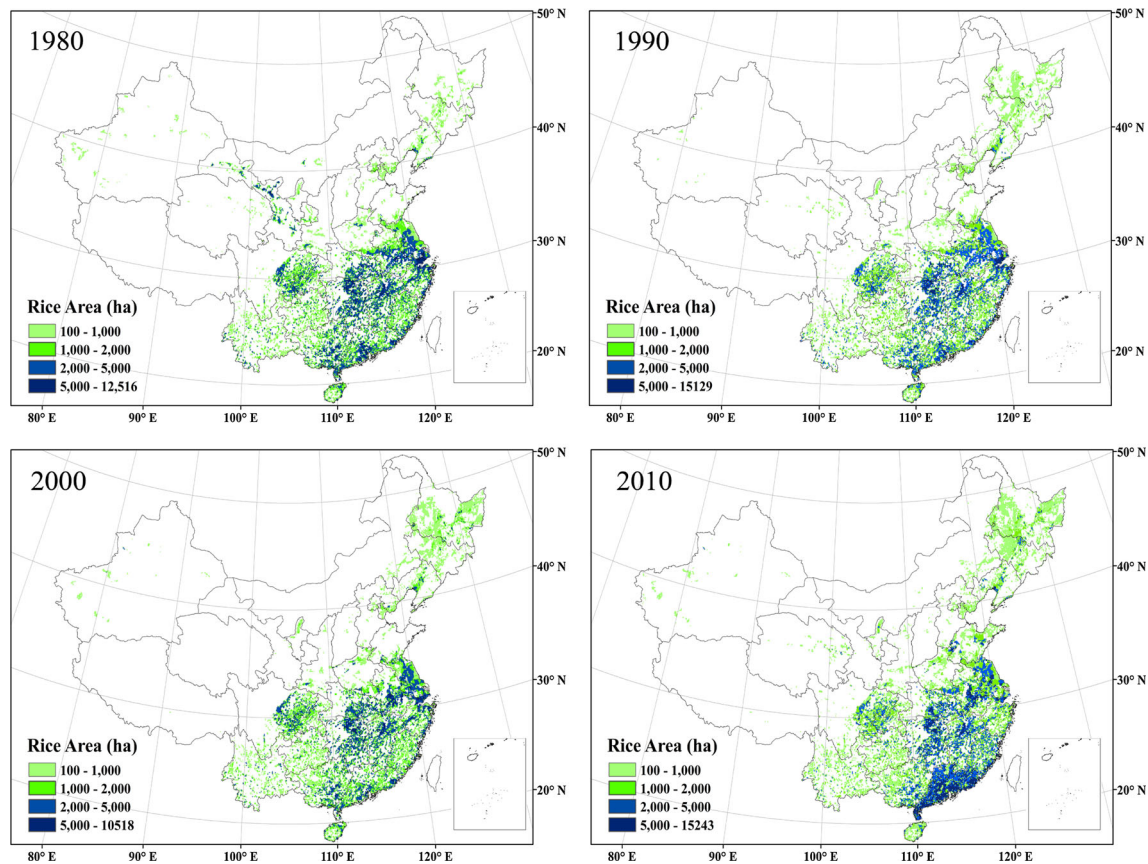


Fig. 2 Spatial distribution of actual rice area in China from 1980 to 2010

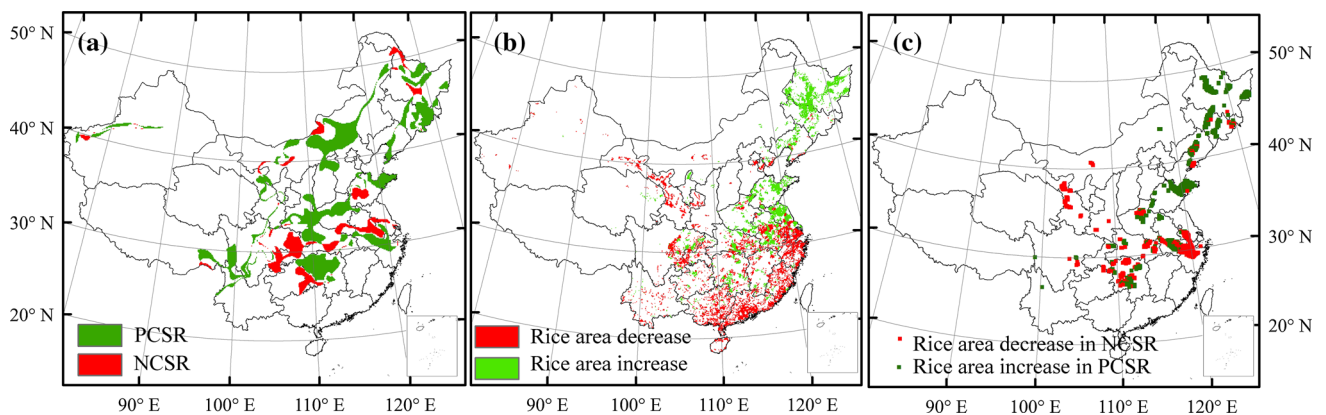


Fig. 3 Extent and location of changes to climatically suitable region of rice (CSRR) (a), actual rice area (b) and the response of actual rice area (c) in China from 1980 to 2010

The increase in actual rice area in the stable LSR indicates that a spatial lag in the adaptation of actual rice area to climate change occurred after 1990. Actual rice area in this region increased by 8.6×10^4 ha during 1980–1990; increased by 2.1×10^5 ha in 1990–2000; and decreased by 1.5×10^5 ha in 2000–2010. The shift from UR to LSR expanded the planting area until the start of the twenty-first century, which may be that farmers' adaption and other

factors are crucial to actual rice area change in this unstable climate region. The actual rice area has decreased by 5415 ha, accounting for -16% , during 1980–1990; decreased by 519 ha, accounting for -1.7% , in 1990–2000; and decreased by 6691 ha, accounting for 14.1% , in 2000–2010 (Table 5).

In the changed PCSR, the actual rice area has increased by 11.4×10^4 ha, accounting for 4.9% , during

Table 4 Summary of pixels with increased and decreased rice area in climatically suitable regions from 1980 to 2010

Types of CSRR	Pixels with increased rice area		Pixels with decreased rice area	
	Pixel number	Percentage (%)	Pixel number	Percentage (%)
PCSR	661	18.2	661	10.1
NCSR	386	10.6	386	10.1
Unchanged LSR	1155	31.9	1155	7.6
Unchanged MSR	1257	34.7	1257	64.5
Unchanged HSR	166	4.6	166	7.8

CSRR climatically suitable region of rice, LSR low climatically suitable region, MSR moderate climatically suitable region, HSR high climatically suitable region, PCSR positive climate-sensitive regions, NCSR negative climate-sensitive region

Table 5 Changes of actual rice area in climatically suitable regions from 1980 to 2010

Period	Types of CSRR	Actual rice area ($\times 10^4$ ha)	Changes of actual rice area ($\times 10^4$ ha)	Changes in the proportion (%)
1980–1990	Unchanged LSR	91.8	8.66	9.4
	UR shift to LSR	3.39	−0.54	−16.0
	PCSR	232	11.4	4.9
	NCSR	273	−7.34	−2.7
1990–2000	Unchanged LSR	49.1	21.2	43.1
	UR shift to LSR	3.02	−0.05	−1.7
	PCSR	37.1	−0.11	−0.3
	NCSR	84.1	2.77	3.3
2000–2010	Unchanged LSR	75.8	14.9	19.7
	UR shift to LSR	4.73	0.67	14.1
	PCSR	143	−6.56	−4.6
	NCSR	412	52.7	12.8

CSRR climatically suitable region of rice, LSR low climatically suitable region, PCSR positive climate-sensitive regions, NCSR negative climate-sensitive region

1980–1990; decreased by 1143 ha, accounting for −0.3 %, in 1990–2000; and decreased by 6.6×10^4 ha, accounting for −4.6 %, in 2000–2010. In the changed NCSR, actual rice area decreased by 7.3×10^4 ha, accounting for 2.7 %, during 1980–1990; increased by 2.8×10^4 ha, accounting for 3.3 %, in 1990–2000; and increased by 5.3×10^5 ha, accounting for 12.8 %, in 2000–2010 (Table 5).

Discussions

Climate warming at high latitudes is clearly evident, especially in northeast China, Heilongjiang Province, where the average minimum temperature is now 2.5°C higher than in the 1960s (Sun et al. 2006). The Intergovernmental Panel on Climate Change (IPCC) has indicated that the high-latitude areas of the Northern Hemisphere are the most susceptible to climate change and suggested that by the middle of this century in northern China, double-planting regions will move toward the existing single-planting areas (Cruz et al. 2007). The present results indicate that climate change was a possible factor underlying the geospatial and temporal changes of rice cropping areas in China; however, in some regions, such as the northeast of China, climate change can influence the pattern of rice expansion. Approximately 18.2 % of the increased rice cropping area in this region was influenced by change to a more suitable climate, which supports the view that agriculture can adapt to climate warming (Olmstead and Rhode 2011). The opposite pattern, where farmers reduce crop areas under newly unsuitable climatic conditions, has been observed in the warmest zones of Europe (Olesen et al. 2011).

Rice is a crop that requires a certain quantity of energy for its cultivation and survival (Gao and Liu 2011). As many studies have indicated that no southern limit exists for rice in China, the northern limit of rice is of greater concern to agricultural management (Yun et al. 2005). The northern limit of Chinese rice production has moved northward from N47° to N52° (Piao et al. 2010; Zhu et al. 2008). Previous research on climatically suitable crop areas has often considered potential area change only while ignoring the actual area change. As has been reported in previous works on potential crop area change, there are many areas, especially in the northern NEC, where rice can now be planted due to climate change; however, these areas were not found to have experienced large increases in actual rice areas in this study. Possible reasons for that are that there are also other effects of climate change such as the increased occurrence of droughts, heat waves and dust storms affecting agriculture negatively in this area. The adaptation of rice cropping systems is a progressive process also influenced by non-climatic factors such as farming practices and market demands.

MaxEnt models are extensively used in species modeling (Phillips et al. 2009) to forecast the distributional changes associated with climate change/land transformation (Elith et al. 2011; Yesson and Culham 2006) in crops such as rice (Duan and Zhou 2013) and banana (Machovina and Feeley 2013). Therefore, the MaxEnt model is a useful tool for modeling the climatically suitable geographical extent of rice (Beck 2013). The climate data used as

environmental variables in this study limited the accuracy of the modeling results, as the spatial resolution of $5' \times 5'$, which is consistent with the SPAM results, was not spatially explicit of the potential changes at a coarse resolution. The species distribution model indicated that climate change has caused large shifts in the locations and extents of the areas that are suitable for rice over the past three decades. Many factors impact the increases and decreases of cropping area, such as irrigation (Döll 2002), new cultivars, crop management (Ortiz et al. 2008), labor shift, market, changes in transport infrastructure and urbanization; however, there is a shortcoming on a quantitatively assessment (Tong et al. 2003). Given the scale and importance of rice production in China, these shifts in suitable land areas have large effects on the local and national agricultural economies.

SPAM was employed to model the distribution of actual rice area at a large scale, but the accuracy of the model results needs widespread assessment; however, until a more comprehensive analysis is developed, the current approach provides the most accurate estimate of crop distributions at the national or global scale (You et al. 2014). New technologies such as remote sensing would be valuable for exploring the spatial heterogeneity of rice distribution, especially at high spatial resolution (Xiao et al. 2005); however, studies relying on remote sensing are limited by high costs and the lack of a historical time series using the method (Peng et al. 2011). The change of cropping patterns over time is as important as that of cropping patterns over space (You et al. 2014), and further application of this model should therefore give greater consideration to spatial and temporal resolution, as the current work employed only a fixed spatial resolution of 5 min at the national or global scale.

Traditional analyses of climate change and crop patterns based on site data are less able to observe spatial impacts, as they omit the spatial climate change that can also change the crop pattern in the cropping area (Tao et al. 2006). Therefore, in this analysis, climate change was considered both spatially and temporally at the national scale. Climate change has complex impacts on the cropping pattern, and only the linkage between climate change and rice cropping area change was analyzed; the mechanism of climate change as a driving force on cropping area change was not considered.

Conclusions

In this study, a species distribution model and a spatial allocation production model were employed to analyze the changes in the potential and actual rice areas of China in the context of climate change. Over the past three decades,

significant climate warming has occurred in China, which has led to an increase in the climatically suitable area for rice in northern China. Approximately 3.9 % of all Chinese land area (approximately 3.7×10^7 ha) has become suitable for rice due to climate change over the past three decades. The increase of heat resources and changes in other climate condition has allowed these areas to be planted with rice as farmers adapt to a longer rice-growing season. Rice area expanded over the study period until 2000 as the climatically unsuitable region shifted to climatically suitable region; it should be noted that the rice area increase is determined not only by climate conditions but also by farmer attitudes, crop management, cultivar replacement, market price, etc. Approximately 18.2 % of the increased rice cropping area occurred in the newly suitable areas of the northern single-cropping rice system, indicating that the shifts in the extent and location of the rice cropping area partly matched the climate change pattern. The evidence from the spatial and temporal changes of actual rice area in the newly climatically suitable region during 1980–2010 indicates that the response of rice cultivation incurs a spatial and temporal lag in response to climate change. Therefore, climate change was one factor underlying the geospatial and temporal changes of rice cropping area in China. To improve rice production in northeast China, many other factors besides area must be considered, such as the replacement of late-maturing cultivars with early-maturing varieties and the improvement of farmer attitudes.

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