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Chinese Rice Production Area Adaptations to Climate Changes, 1949–2010

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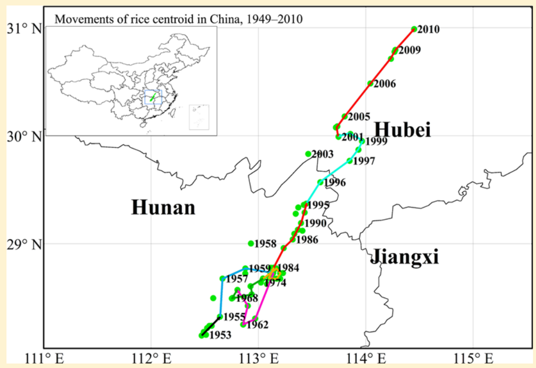
S Supporting Information

ABSTRACT: Climate change has great impact on cropping system. Understanding how the rice production system has historically responded to external forces, both natural and anthropogenic, will provide critical insights into how the system is likely to respond in the future. The observed historic rice movement provides insights into the capability of the rice production system to adapt to climate changes. Using province-level rice production data and historic climate records, here we show that the centroid of Chinese rice production shifted northeastward over 370km (2.98°N in latitude and 1.88°E in longitude) from 1949 to 2010. Using a linear regression model, we examined the driving factors, in particular climate, behind such rice production movement. While the major driving forces of the rice relocation are such social economic factors as urbanization, irrigation investment, and agricultural or land use policy changes, climate plays a significant role as well. We found that temperature has been a significant and coherent influence on moving the rice center in China and precipitation has had a significant but less spatially coherent influence.



■ INTRODUCTION

China is the largest producer and consumer of rice in the world. With a population of 1.3 billion people, providing enough of this staple food is a challenge in China, and climate change is expected to exacerbate existing problems due to its projected adverse impact on both rice productivity and the area suitable for rice production.[1−3] Changes to China's rice producing capacity will have implications for food security, both regionally and globally. Rice is the staple food for more than 65% of the Chinese population, and China accounts for 19% of the world's total rice production.[4,5] The areas used for rice production in China have changed over the last six decades, total production has increased, and significant geographic shifts have occurred.[4] Understanding how the rice production system has historically responded to external forces, both natural and anthropogenic, will provide critical insights into how the system is likely to respond in the future.[6] The rice production system in China has displayed fluctuating planted areas, increasing total production, and significant geographic shifts over the last half-century. Between 1949 and 2010, the annual planted area of rice in China increased from 25.7 to 29.6 million hectares but the peak was 36.2 million hectares in 1976. Yields, however, went up from 1892 kg per hectare in 1949 to 6553 kg per hectare in 2010 (Supporting Information (SI) Figure S1). Due to these increasing yields on varying rice planted areas, annual Chinese rice production has been fairly stable at 170–200 million tons since 1984. The geographic location of that production, however, has changed considerably.

Current analyses aimed at improving food security often focus on yields. Understanding how the areas planted with rice have changed—both in terms of their extent and their geographic location—has implications for food security and resource management that are not shown by yield analyses alone.[5,6] For example, the location and extent of the rice growing areas are critical if natural resources, which may be costly, if not impossible, to transport, are to be allocated efficiently. Infrastructure development helps expand or develop natural resources, and may be either a precursor or a response to geographical changes in agriculture. Changes in the rice growing area may have impacts on, and in turn be affected by, the natural ecosystem as well.[7,8] Geographical changes in cultivation may affect regional temperature and precipitation patterns, particularly given that nearly all the rice grown in

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China is irrigated.[9] Less well understood, however, is how long-term changes in temperature and precipitation may drive changes to the extent and location of rice production.

Specifically for China, there are a wide range of estimates of how climate change will impact rice phenology,[10] yield and production,[11−13] but few of them have investigated how planted rice areas have adapted to climate change. Even though technology advances in crop management and crop varieties have largely improved rice yield, there are still considerable gaps in our knowledge about how rice cropping systems will be affected by both short-term and long-term climatic changes.[14,15] In the northeast of China where rice expanded quickly, climate warming has prolonged the growing season, the northward movement of accumulated temperature belts, and the decrease of cold stress.[3] Warming has enabled a significant northward expansion of rice planting in Heilongjiang Province, a northward shift from about 48°N to approximately 52°N.[16]

This study aimed to fill this research gap. First, we quantified, using a centroid method, the rice production dynamic movement from 1949 to 2010. Then we evaluated, using a linear regression model, the driving factors of such rice movement, in particular the impact of climate on the rice production changes. We further discussed the policy implications of our findings on climate change adaptation and on agricultural R&D investment.

■ DATA SOURCES AND METHODOLOGY

Data Sources. The data of rice sown area data covers the period of 1949−2010, and other social economic and climatic variables covers the period of 1980 to 2010 for 27 major rice producing provinces in China. The county level data of climate records from 1980 to 2010 was obtained from the Chinese's Meteorological Administration (CMA), and details of climate data can be seen in SI Section S1 and Section S2. Observed climate stations and rice growing area in China in 2010 are shown in SI Figure S2. The rest of the data sets are taken from various statistics books such as China Statistical Yearbook (1971−2011) and China Rural Statistical Yearbook (1971−2011) published by China's National Statistical Bureau,[17,18] the Sixty Years Agricultural Statistics of China (1949−2008) by Ministry of Agriculture of China.[19]

Rice Centroid Calculation. We used the centroid method to calculate the geographical centroid of China's rice production area.[4] The model looks at the dynamics of the centroid during the period examined and estimates the location (longitude, X_t and latitude, Y_t) of the centroid of Chinese rice production area.

$$X_t = \frac{\sum_{i=1}^{n} (A_{i,t} \times X_i)}{\sum_{i=1}^{n} A_{i,t}};\ Y_t = \frac{\sum_{i=1}^{n} (A_{i,t} \times Y_i)}{\sum_{i=1}^{n} A_{i,t}} \quad (1)$$

X_i and Y_i are the longitude and latitude of the geographical centroid of province i; $A_{i,t}$ is the rice planted area for year t in province i; n is the total number of rice producing provinces (n = 27).

Linear Regression Model. Change of crop production area is an important part of land use and land cover change.[20,21] There are various factors driving the relocation of crop production. These include biophysical factors and socio-economic factors, such as climate warming in northeast China and rapid urbanization in southeast China (particularly in the Pearl River and the Yangzi River Delta areas). There have also been technological improvements to rice seeds, increased irrigation, mechanization and fertilizer use, and dramatic agricultural policy changes over the last 30 years in China.[22−24] To investigate the extent to which each of these factors influenced rice production change, we estimated the changes caused by a number of individual factors using a regression model. Such econometric model is widely used in economics literature. Here we build a linear regression model with a log transform as the variables are all positive and continuous (except cropping intensity)

$$\log(A_{i,t}) = \sum_j \alpha_j \log(X_{i,j,t}) + \sum_j \beta_j \log(\mathrm{Clim\ ate}_{i,j,t}) + \sum_r \delta_r D_r + \varepsilon_{i,t} \quad (2)$$

where $A_{i,t}$ is the rice production area in province i at year t; $X_{i,j,t}$ represents nonclimatic factors in province i at year t, which include agricultural gross domestic product (AgGDP), energy consumption per hectare cultivated land, irrigated area, total crop value, arable land per rural population, the proportion of urban population and the rice cropping intensity. $Climate_{i,j,t}$ represent the climate variables, which are temperature and rainfall during the rice growing season for province i at year t and temperature and rainfall during rice growing season for province i at previous year ($t-1$). We have included a set of regional dummy variables, D_r, which represent the time-persistent, regional differences in social, economic and natural parameters that are not accounted for by other variables. Similarly, a set of time dummies, D_t, were considered as a means of capturing the effects of a few major policy reforms in agriculture during this period; however, the time dummy variables had little effect on the model and so were excluded for the sake of minimizing model complexity. We hypothesize that AgGDP, irrigation, total crop value, land per capita all would have positive impact on rice area while urbanization would have negative effect. The estimated parameters are α_j, β_j and δ_r, and $\varepsilon_{i,t}$ is the error term. We run this model with the standard STATA package (http://www.stata.com/). We have validated the model and found little difference with various robustness tests and different function forms (SI, Section S3). The model including time dummy variables and different function forms and associated results can be found in the SI (Table S3 and S4, Figure S3, S4, S5, S6, and S7).

Climate Impact Isolation. We investigate the impacts that climate variables (temperature, precipitation or both) had on moving the geographical centroid of rice production area by calculating the climate-associated variations for province i and year t using

$$\mathrm{HA}_{i,t}^{C} = ncA_{i,1981} + \beta(C_{i,t}) + \beta(C_{i,t-1}) \quad (3)$$

where $\mathrm{HA}_{i,t}^{C}$ is the hypothetical area for province i and year t in the event that only climate variables changed from 1981 levels, C is the climate variable of interest (temperature, precipitation or both) and the β's are the associated coefficients estimated in eq 1. nc$A$ is the nonclimate influenced area for province i, which is defined as

$$\mathrm{nc}A_{i,1981} = A_{i,1981} - \beta(C_{i,1981}) - \beta(C_{i,1980}) \quad (4)$$

where A is the actual planted area of rice in 1981 for province i.

To isolate the impact of climate on the centroid of rice production in each year, we first calculated the hypothetical rice area using eq 1 by holding all variables constant at 1981 levels, with the exception of the climate variables (See eqs 3 and 4).

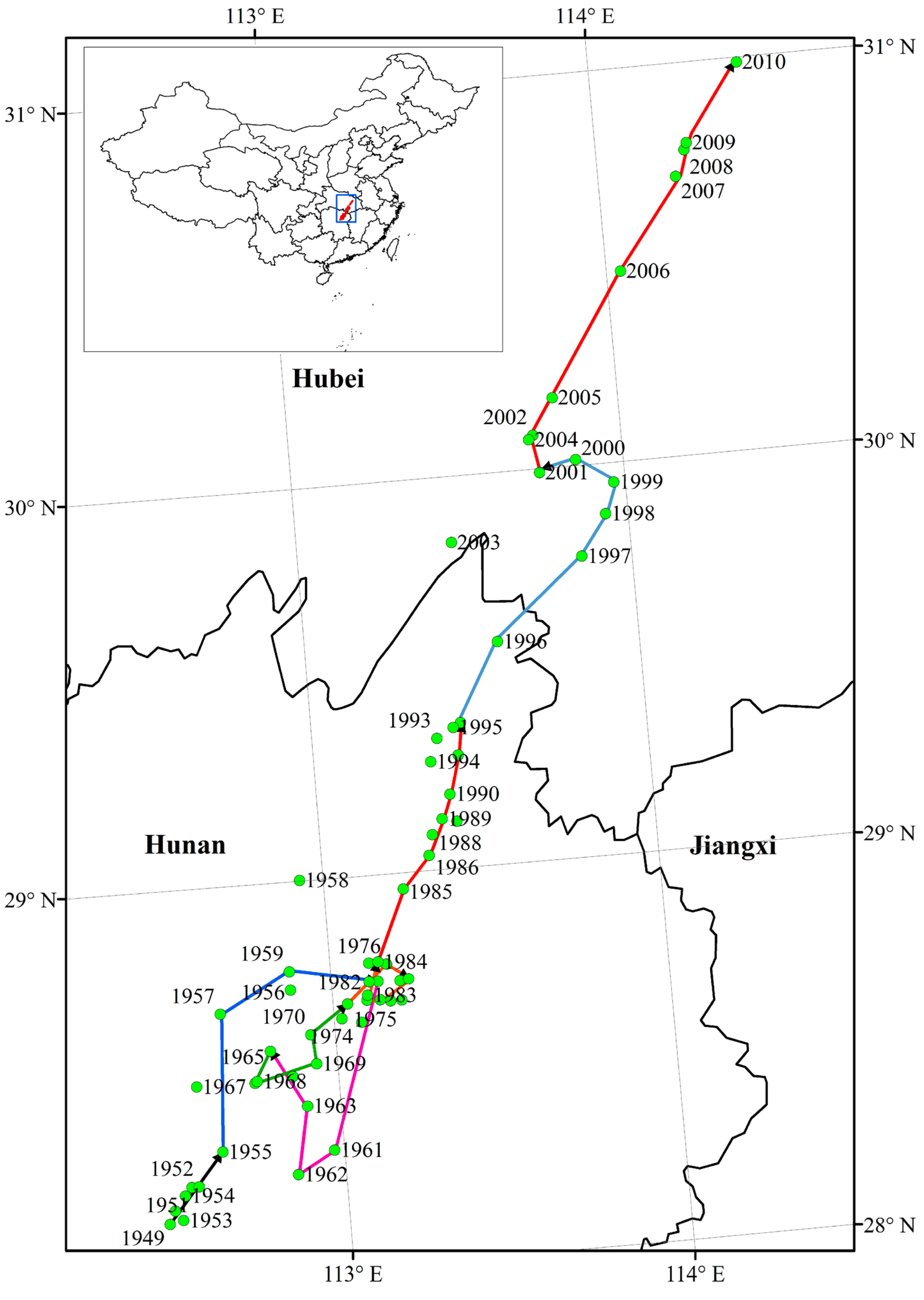

Figure 1. Movements of the geographical centroid of rice production between 1949 and 2010. (Dark line: 1949−1954; First blue line: 1955−1959; Pink line: 1960−1965; Green line: 1966−1984; First red line: 1984−1994; Second blue line: 1995−2000, Second red line: 2001−2010).

This provides a comparative analysis of how we might expect the centroid of rice production to have changed in the event that climate was the only influencing factor. While this construction is not informative in equation-form, once the centroid is calculated and plotted, the resulting scatter of the climate-only variations can be compared to the historical movement, which visually represents the isolated impact of climate-only on the geographical centroid of rice production.

■ RESULTS AND DISCUSSION

Relocation of Rice Centroid. The rice production area in China increased between 1949 and 1981 at an annual rate of 0.9%, but decreased between 1981 and 2010 at an annual rate of −0.62% (see SI Table S1). The spatial distribution has also varied considerably over the six decades. We have quantified the variation by estimating the movement of the geographical centroid of China's rice production. Figure 1 shows the movements of the rice geographical centroid since 1949. The

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largest proportion of agricultural land used for rice production (95%) was in southern China in 1949 (dark line in Figure 1). By 2010, however, the centroid of rice production area had moved 370 km to northeast (latitude 2.98°N, longitude 1.88°E) from central Hunan Province into northeast Hubei Province. The majority of these geographical movements occurred after 1984 when the Household Responsibility System (HRS) was gradually introduced in China.[25] Under HRS, Chinese farmers could decide for themselves what to plant and how to manage their agricultural production, based on their own understanding of the soil/water conditions and market demands.[26] This led to dramatic changes in both rice cropping systems and productivity. The rice centroid moved 93.4 km north at a speed of 2.59 km/year between 1966 and 1984 (green line in Figure 1), and 262 km north at a speed of 10.5 km/year from 1984 to 1994 (first red line in Figure 1) when the HRS had been completely implemented. Rice relocation most dramatically shifted in the 2000s, as illustrated by the long-stretched line from 2001 to 2010 (second red line in Figure 1). Rice production area expanded significantly in northeast China and rice is now grown as far north as Heilongjiang province due to the higher temperatures.[16] However, in southern China (south of 32°N) the rice area decreased between 1960 and 1965 (pink line in Figure 1), because the Double Rice Cropping System (DRCS) became widespread in southern China in the 1960s. This new cropping system increased land-use efficiency, raised crop production, and reduced agriculture land use.

Factors Driving Rice Production Area Change. Due to data availability of the independent variables, we could only run the above model from 1980 to 2010. This is also the period when the dramatic change of Chinese rice relocation occurred (Figure 1). Table 1 shows the regression results. The major socio-economic driving factors to increase rice production area were irrigation, cropping intensity, rice prices, per capita arable land value, and AgGDP, whereas energy consumption and urbanization had a negative effect on the rice production area. Irrigation made the largest positive contribution to the increase in rice production area (each 1% increase in irrigated area increased the rice production area by over 0.7%). Irrigation can significantly improve the conditions for rice cultivation, and its introduction into northeastern of China, which formerly lacked of irrigation, significantly increased the rice production in this region.. As expected, AgGDP, the value of crop production and per capita arable land all have positive effect on rice area, whereas urbanization has a negative effect. Energy use per hectare arable land had a large negative impact on the rice area (each 1% increase in energy consumption decreased rice production area by almost 0.4%). The large negative effect may relate to the decreasing rice cultivation and rising use of machinery in coastal regions. Both temperature and precipitation positively influenced rice production area. As might be expected, the previous season's temperature and precipitation was a good predictor of the current season's temperature or precipitation, and both had significant influences on the increase in rice production area. Each 1% increase in growing season temperature increased rice production area by nearly 3%, whereas a 1% increase in precipitation led to a 0.3% increase in rice production area, which was much smaller than the temperature effect.

Table 1. Estimated Rice Area Function for China, 1980–2010[a]

explanatory variables	estimated coefficients	*t*-values
constant	−25.041***	−11.397
log (AgGDP)	0.0385	0.760
log (irrigation)	0.7018***	9.664
log (energy)	−0.3690***	−6.662
log (crop value)	0.1955*	0.735
log (urbanization)	−0.0169	−0.199
log (arable land/rural person)	0.1573*	2.040
log (previous growing season temperature)	2.9456***	4.799
log (growing season temperature)	3.0306***	4.951
log (previous growing season precipitation)	0.3413**	3.022
log (growing season precipitation)	0.3162**	2.762
double cropping	0.6351**	3.237
degree of freedom	792	
adjusted R^2	0.905	

[a]There is a $\log(y) \sim\beta \log(x)$ relationship with no yearly fixed effects. *, **, and *** represent 0.1, 0.05, and 0.01 levels of statistical significance, respectively.

Climate Impact on Relocation of Rice Centroid. The impact of climate on the relocation of rice centroid is shown in Figure 2. The top panel (A) demonstrates the trends in rice production area by province, as well as the historical movement of the geographical centroid of rice production. The lower three panels demonstrate what the relocation of rice production centroid would look like if the only variable that changed from 1981 levels was precipitation (panel B), temperature (panel C), or both temperature and precipitation (panel D). Figure 2 demonstrates that although there seems to be little coherency in the trend arising from precipitation, the influence of temperature has a clear northeastward influence on the relocation of rice production. When both temperature and precipitation varied together, the geographical centroid of rice production results show a clear west-to-east movement and a minor south-to-north pattern (Figure 2, panel D). The less coherent impact of precipitation on rice relocation was expected as rice in China is almost always irrigated,[5] which would compensate for rainfall deficiencies. This was further confirmed by the significant and clear impact of irrigation on the geographical centroid of rice production (see SI Figure S8 (C)).

These results were supported by an analysis of the area trends and average growing-area-weighted trends in climate variables (see SI Figure S9). Temperature had a fairly coherent trend, and moved the rice production area from the southwest to the northeast. The average rice growing season temperature by 2010 in Heilongjiang was over 2 °C higher than it was in the early 1950s (see SI Figure S9, panel A). Although the area-weighted temperature trend pattern showed that temperature rose fastest in the southeast, the trends in the northeast were also significant and a west-east longitudinal gradient persisted regardless of latitude (see SI Figure S9, panel B). The lack of a coherent spatial precipitation influence reflected the mixed influence of precipitation in the largest areas of rice cultivation. There was a fairly coherent pattern of declining rains in the north of China during the growing season (see SI Figure S9, panel C), but a much less clear spatial pattern for the area-weighted precipitation trends (see SI Figure S9, panel D).

We have quantified the centroid movement of rice production area in China for the last six decades, and further evaluated the driving factors behind such movement. The

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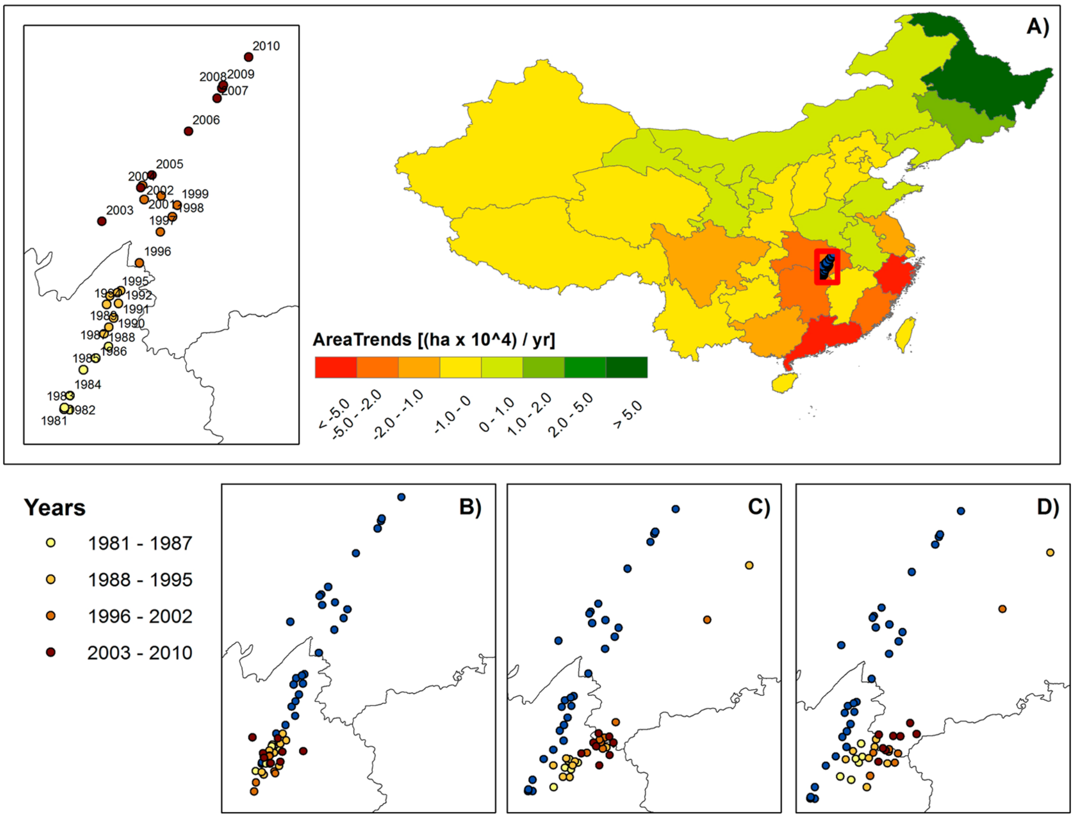

Figure 2. Historical and hypothetical trends for the centroid of rice production in China, which have a $\log(y) \sim \log(x)$ relationship. (A) historical changes; (B) changes due to precipitation alone; (C) changes due to temperature alone; and (D) changes due to both precipitation and temperature.

impact analysis was developed to quantify the extent to which each of the biophysical, socio-economic, and technological factors influenced rice production area change. Climate change also had a significant effect on relocation and expansion of rice production area. In particular, we found temperature has a clear northeastward influence on the relocation of rice production, which meant that climate warming in the north pushed the rice production frontier northwards and farmers relocated their rice cultivation in response to the changing climate. However, the influence of precipitation was less spatially coherent than temperature, because irrigation compensated for rainfall deficiencies.

Our study has shown that rice cultivation has been moving northward since 1940s and such movement is accelerating in the last few decades. While rapid urbanization (in particular in coastal region), Chinese agricultural and land use policy changes, mechanization, and farming management, and many other factors drive such rice movement, climate change plays a significant role. Warming climate in the north has pushed the rice production frontier to the north. Farmers relocated their rice cultivation as a response to the changing climate. China's agriculture would face enormous challenging with the impending climate change. Understanding the self-adjustment capacity of rice production system is critical for both estimating the economic impacts and designing adaptation strategy of future climate change. Given the long lags between agricultural R&D investment and their payoffs, wider and deeper research into cropping system's adaptation to climatic change, and public investment for research in agricultural adaptability in general should be a policy priority.[26,27]

ASSOCIATED CONTENT

Supporting Information

Additional information as noted in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Peng, S.; Huang, J.; Sheehy, J. E.; Laza, R. C.; Visperas, R. M.; Zhong, X.; Centeno, G. S.; Khush, G. S.; Cassman, K. G. Rice yields

decline with higher night temperature from global warming. *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 9971−9975.

(2) Lobell, D. B.; Burke, M. B.; Tebaldi, C.; Mastrandrea, M. D.; Falcon, W. P.; Naylor, R. L. Prioritizing climate change adaptation needs for food security in 2030. *Science* **2008**, *319* (5863), 607−610.

(3) Yang, X.; Lin, E.; Ma, S.; Ju, H.; Gao, L.; Xiong, W.; Li, Y.; Xu, Y. Adaptation of agriculture to warming in Northeast China. *Clim. Change* **2007**, *84* (1), 45−58.

(4) Liu, Z.; Li, Z. G.; Tang, P.; Li, Z. P.; Wu, W.; Yang, P.; You, L.; Tang, H. Changes analysis of rice area and production in China during the past three decades. *J.Geogr. Sci.* **2013**, *23* (6), 1005−1018.

(5) You, L. A tale of two countries: Spatial and temporal patterns of rice productivity in China and Brazil. *China Econ. Rev.* **2012**, *23* (3), 690−703.

(6) Wu, W.; Verburg, P. H.; Tang, H. Climate change and the food production system: Impacts and adaptation in China. *Reg. Environ. Change* **2014**, *14* (1), 1−5.

(7) Piao, S.; Ciais, P.; Huang, Y.; Shen, Z.; Peng, S.; Li, J.; Zhou, L.; Liu, H.; Ma, Y.; Ding, Y.; Friedlingstein, P.; Liu, C.; Tan, K.; Yu, Y.; Zhang, T.; Fang, J. The impacts of climate change on water resources and agriculture in China. *Nature* **2010**, *467*, 43−51.

(8) Ramankutty, N.; Delire, C.; Snyder, P. Feedbacks between agriculture and climate: An illustration of the potential unintended consequences of human land use activities. *Global Planet Change* **2005**, *54*, 19−93.

(9) Tao, F.; Yokozawa, M.; Xu, Y.; Hayashi, Y.; Zhang, Z. Climate changes and trends in phenology and yields of field crops in China, 1981−2000. *Agric. For.Meteorol.* **2006**, *138* (1), 82−92.

(10) Zhang, T.; Huang, Y.; Yang, X. Climate warming over the past three decades has shortened rice growth duration in China and cultivar shifts have further accelerated the process for late rice. *Global Change Biol.* **2013**, *19* (2), 563−570.

(11) Lobell, D. B.; Field, C. B. Global scale climate−crop yield relationships and the impacts of recent warming. *Environ. Res. Lett.* **2007**, *2* (1), 1−7.

(12) Yu, Y.; Huang, Y.; Zhang, W. Changes in rice yield in China since 1980 associated with cultivar improvement, climate and crop management. *Field Crops Res.* **2012**, *136*, 65−75.

(13) Tao, F.; Yokozawa, M.; Liu, J. Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Clim. Res.* **2008**, *38*, 83−94.

(14) Wassmann, R.; Jagadish, S. V. K.; Heuer, S.; Ismail, A. M.; Redona, E.; Serraj, R.; Singh, R. K.; Howell, G.; Pathak, H.; Sumfleth, K. Climate change affecting rice production: The physiological and agronomic basis for possible adaptation strategies. *Adv. Agron.* **2009**, *101*, 59−122.

(15) Yao, F.; Xu, Y.; Lin, E.; Yokozawa, M.; Zhang, J. Assessing the impacts of climate change on rice yields in the main rice areas of China. *Clim. Change* **2007**, *80* (3−4), 395−409.

(16) Gao, J.; Liu, Y. Climate warming and land use change in Heilongjiang Province, Northeast China. *Appl. Geogr.* **2011**, *31*, 476−482.

(17) National Bureau of Statistics of China (NBS). *China Statistical Yearbook*; China Statistics Press: Beijing, China, 1971−2011 (in Chinese).

(18) National Bureau of Statistics of China (NBS). *China Rural Statistical Yearbook*; China Statistics Press: Beijing, China, 1971−2011 (in Chinese).

(19) Ministry of Agriculture of the People's Republic of China. *Agricultural Statistics of New China in Sixty Years (1949−2008)*; Agricultural Press: Beijing, China, 2009 (in Chinese).

(20) Beddow, J. M.; Pardey, P. G.; Koo, J.; Wood, S. *The Shifting Patterns of Agricultural Production and Productivity Worldwide*; The Midwest Agribusiness Trade Research and Information Center, Iowa State University: Ames, IA, 2010; pp 7−38.

(21) Verburg, P. H.; Neumann, K.; Nol, L. Challenges in using land use and land cover data for global change studies. *Glob Change Biol.* **2011**, *17* (2), 974−989.

(22) Chen, C.; Qian, C.; Deng, A.; Zhang, W. Progressive and active adaptations of cropping system to climate change in Northeast China. *Eur. J. Agron.* **2012**, *38*, 94−103.

(23) Tong, C.; Hall, C. A. S.; Wang, H. Land use change in rice, wheat and maize production in China (1961−1998). *Agric. Ecosyst. Environ.* **2003**, *95*, 523−536.

(24) You, L.; Spoor, M.; Ulimwengu, J.; Zhang, S. Land use change and environmental stress of wheat, rice and corn production in China. *China Econ. Rev.* **2011**, *22*, 461−473.

(25) Lin, J. Y. Rural reforms and agricultural growth in China. *Am. Econ. Rev.* **1992**, *82*, 34−51.

(26) Lin, G. C. S.; Ho, S. P. S. China's land resources and land-use change: Insights from the 1996 land survey. *Land Use Policy* **2003**, *20* (2), 87−107.

(27) Alston, J. M.; Beddow, J. M.; Pardey, P. G. Agriculture, agricultural research, productivity, and food prices in the long run. *Science* **2009**, *325*, 1209−1210.

(28) Tao, F.; Yokozawa, M.; Xu, Y.; Hayashi, Y.; Zhang, Z. Climate changes and trends in phenology and yields of field crops in China, 1981−2000. *Agric. For. Meteorol.* **2006**, *138* (1), 82−92.

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