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Rice production and climate change in Northeast China: evidence of adaptation through land use shifts

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Abstract

Climate change continues to have a great impact on rice production in China, especially in Northeast China (NEC). Historical climate observations from the China Meteorological Administration and statistical agricultural records at the county level were utilized to evaluate the spatial and temporal effects of both climatic and socioeconomic factors on rice production between 1980 and 2010 in NEC by using a linear regression model. The results showed that a 1% increase in the accumulated temperature (RAT) significantly increases rice production by approximately 0.728%. Rising RAT over the past three decades increased rice production by 4.44% (equal to a relative contribution of 0.87% to production growth) in NEC, while the majority of rice production growth (79.6%) resulted from increased agricultural inputs. Furthermore, rice production has increased significantly since 2000, and its geographic centroid shifted over 320 km northeastward during the past 30 years. Historical statistical and simulated rice production data for each county were used to quantify the spatial relocation of rice production due to single climatic factors. During 1980–2010, temperature had a significant and coherent influence on moving rice production. The impact of growing season precipitation was not significant, while sunshine had a significant but less spatially coherent influence. Our findings highlight the response of the rice production system to external driving factors, both climatic and socioeconomics, to target further research and provide important insights into how a rice cropping system is likely to adapt in a mid-high-latitude region in the future.

Introduction

Rice is the staple food for more than 65% of the Chinese population (Li et al 2015) and is playing an important role in ensuring food security in China (You 2012, Liu et al 2013a). However, it is expected that climate change will exacerbate the existing problem due to its projected adverse impact on both rice productivity and the planting area suitable for rice production (Peng et al 2004, Yang et al 2007, Lobell et al 2008 and 2011). Therefore, understanding changes to China’s rice production will have important implications for food security and crop production adaptation to climate change, both regionally and globally.

Aimed at improving food security, current analyses often focus on rice yield. It is widely accepted that technological advances in crop management and crop varieties have significantly improved rice yield (Lobell and Field 2007, Yu et al 2012). The effect of climatic warming on rice yield has been investigated, but the results are still ambiguous (Lobell et al 2011, Liu et al...
driving factors vary at the regional, and global scales (You et al. 2011). However, the amount of change in rice production due to socioeconomic factors and climate change is still unknown, especially on a large scale; the characteristics of climate change that improve rice relocation remain unclear.

Therefore, this study focuses on the NEC region, and the main objectives of this study are (1) to investigate the relocation of the geographical center of NEC rice production; (2) to analyze the extent to which each of the driving factors influenced rice production changes; (3) to identify the relative contribution of each factor to rice production; and (4) to explore the direct impact of climatic factors (temperature, precipitation and sunshine) on the geographic center of rice production.

Materials and methods

Data

Historical data on rice production between 1980 and 2010 for 161 counties in NEC (figure 1 and table S1) is available online at stacks.iop.org/ERL/14/024014/mmedia were collected from the Planting Information Network of China (PINC 2014). County-level data of socioeconomic variables (supplementary information (SI) and table S1) were obtained from various statistical books, such as the China Statistical Yearbook (1980—2010) and China Rural Statistical Yearbook (1980—2010), published by China’s National Statistical Bureau (NBSC 2011a, 2011b), and the Agricultural Statistics of China (1980—2008), published by the Ministry of Agriculture of China (MOA 2009).

Historical daily weather data, including the mean temperature, precipitation and sunshine hours spanning from 1980 to 2010, for 84 meteorological stations in NEC were obtained from the China Meteorological Data Service Centre (http://data.cma.cn/) of the China Meteorological Administration (CMA). The number of weather stations (84 stations) is less than the number of counties (161 counties) in NEC since weather observations were not supplied for each county by the CMA. Therefore, to fulfill the need for climate data at the county scale, we recreated the weather data for 50 km by 50 km grids for each year by using the inverse distance weighted interpolation method (IDW, Shepard 1968) based on the 141 meteorological station records around NEC (figure 1). For the county without a meteorological station, the grid data within the county were selected as weather data.

Rice production function

Crop production is an inherently spatial process, with output being greatly influenced by biophysical and socioeconomic factors (Alston et al. 2009, Kukal and Irmak 2018). We hypothesize that some socioeconomic factors (e.g. crop inputs, irrigation and
mechanization) might have positive effects on rice production, while others, such as urbanization, have negative effects on rice production. Biophysical factors (i.e. temperature, precipitation and solar radiation) have complicated effects on rice production. Warming also has enabled a significant northward expansion of rice planting in NEC (Gao and Liu 2011), which positively affects rice area and production. The effect of climate and other biophysical and socioeconomic factors on rice production was estimated by using the following linear rice production model:

$$\ln(P_{i,t}) = \alpha_0 + \alpha_1t + \sum_{m} \beta_m \ln(C_{m,i,t}) + \sum_{k} \gamma_k \ln(E_{k,i,t}) + \sum_{j} \delta_j \ln(X_{j,i,t}) + w \ln(U_{i,t}) + \sum_{r} \mu_r D_r + \sum_{n} \theta_n D_n + \varepsilon_{i,t},$$

(1)

where $\ln$ is the natural log, and $t = 1, 2, \ldots, 31$ denotes the observations from the years 1980–2010. $P_{i,t}$ refers to rice production for NEC county $i$ at year $t$. $C_{m,i,t}$ represents the climate variables, including the accumulated temperature (RAT$_{i,t}$), total precipitation (GSP$_{i,t}$) and total sunshine hours (GSS$_{i,t}$) during the rice growing season (1st May–30th September) (Zhang et al 2013). RAT$_{i,t}$ is calculated as the sum of the daily average temperatures above 10°C (RAT = \( \sum T_j \) if $T_j > 10$°C) for the period with daily average temperatures steadily above 10°C during the rice growing season (Yang et al 2011, Liu et al 2013b). $E$ denotes the vector of socioeconomic variables including the proportion of agricultural GDP in the total GDP of the county (Value), the proportion of rural laborers for crop plantation (Labr) and the proportion of rice area in the total crop area (Spec). $X$ represents the physical inputs per ha of sown rice area, including fertilizer (Fert), pesticide (Pest), mulch (Mulch), machinery (Mach), irrigation area (Irrg), and electricity (Energy); $U$ represents the urban population proportion of the total population (Urban) to reflect the influence of urbanization. More details about these variables are shown in the SI and table S1. The parameters $m$, $k$ and $j$ represent the number of variables for each variable set. We included a set of regional dummy variables ($D_r$) for three provinces (Liaoning, Jilin, and Heilongjiang) to represent time-persistent, regional differences in social, economic, and natural conditions not accounted for by the included variables. The time-specific dummy variables ($D_{it}$) reflect the effects of two major institutional changes. During our study period (1980–2010), NEC implemented two major policy reforms: the Household Responsibility System in the early 1980s and the New Development in Agricultural Policy in the mid-1990s. A time trend ($t$) was used to represent technological change during this period. $\alpha$, $\beta$, $\gamma$, $\delta$, $w$, $\mu$, and $\theta$ are parameters to be estimated, and $\varepsilon$ is the error term. The model is estimated by the Stata package (http://stata.com/). The variance inflation factor (VIF) was used to ensure robust model estimates (SI, table S2), and collinear variables were eliminated if the VIF was higher than 10. The Akaike information criterion (AIC) was used to select the final model from a total of 14 candidate models (SI, table S4). All of the explanatory variables in table 1 passed the tests and were maintained in the regression model.

**Rice production centroid**

The centroid method was used to calculate the geographical centroid of rice production in NEC. The model examines the dynamics of the centroid between 1980 and 2010 and estimates the location (longitude, $X_l$, and latitude, $Y_l$) of the centroid of rice production.
Table 1. Estimated rice production function for Northeast China (NEC), 1980–2010.

| Explanatory variables                  | Estimated coefficients |
|----------------------------------------|------------------------|
| Ln(Value)                              | 0.148*** (7.02)        |
| Ln(Spec)                               | 0.968*** (136.42)      |
| Ln(Labr)                               | 0.071* (2.08)          |
| Ln(Urban)                              | -0.046** (-4)          |
| Ln(Irrg)                               | 0.083*** (5.94)        |
| Ln(Mulch)                              | 0.441*** (21.33)       |
| Ln(Mach)                               | 0.144*** (8.93)        |
| Ln(NP)                                 | 0.015 (1.48)           |
| Ln(Mach)                               | 0.213*** (11.41)       |
| Ln(Energy)                             | 0.025 (1.6)            |
| Ln(RAT)                                | 0.728** (4.46)         |
| Ln(GSP)                                | 0.035 (0.99)           |
| Ln(GSS)                                | 0.302* (2.57)          |
| Time trend                             | 0.007* (2.65)          |
| Regional dummy(HeiLongJiang)          | 0.263*** (8.74)        |
| Regional dummy(HeilongJiang)          | 0.736*** (23.78)       |
| Institutional dummy (1980–1989)        | 0.009 (0.29)           |
| Institutional dummy (2000–2010)        | 0.184*** (7.23)        |
| Constant                               | -4.216** (-2.79)       |
| Adj R-squared                          | 0.941                  |

Note. Standard errors in parentheses. Dependent variable = Ln (rice production).
* p < 0.05; ** p < 0.01; *** p < 0.001.

\[ X_i = \sum_{t=1}^{n}(P_{i,t} \times X_i); \quad Y_i = \sum_{t=1}^{n}(P_{i,t} \times Y_i), \]  

(2)

where \( X_i \) and \( Y_i \) are the longitude and latitude, respectively, of the geographical centroid of county \( i \); \( P_{i,t} \) is the rice production for year \( t \) in county \( i \); and \( n \) is the total number of rice producing counties (\( n = 161 \)).

Relative contributions of factors
To assess the contribution of climate change to rice production, we used the first derivative of equation (1) with respect to \( t \) (You et al. 2009) so that the growth rate of rice production in NEC was expressed as equation (3)

\[ \frac{\Delta \ln(P_{i,t})}{\Delta t} = \alpha_t + \sum_m \beta_m \frac{\Delta \ln(C_{m,i,t})}{\Delta t} + \sum_k \gamma_k \frac{\Delta \ln(E_{k,i,t})}{\Delta t} + \sum_j \delta_j \frac{\Delta \ln(X_{j,i,t})}{\Delta t} + \ln U_{i,t} + \sum_n \eta_n \frac{\Delta D_n}{\Delta t} + \frac{\Delta \varepsilon_{i,t}}{\Delta t}. \]

(3)

The terms on the right side of the equation measure the direct impact of variable changes on rice production and a positive effect indicates that the variable enhances rice production. To characterize the relative contribution of each factor, the growth of rice production was set equal to 100, and then, the each of the right-hand side terms was transformed into the percentage of contribution to production growth. Table 2 reports the growth accounting based on the estimated coefficients of the rice production function in column 3 of table 1. To avoid an atypical year, we take a three-year average value (i.e. 1980–82 and 2008–2010) for each parameter in calculating the total growth from 1980 to 2010.

Climate impact isolation
To isolate the effects of climate variables, we follow Li et al. (2015) and first calculated the predicted rice production by holding all variables constant at the 1980 levels, except for the climate variables

\[ HP_{i,t} = \Delta ncP_{i,1980} + \beta(C_{i,t}), \]  

(4)

where \( HP_{i,t} \) is the predicted rice production for county \( i \) and year \( t \) if only climate variables changed from the 1980 levels. \( C \) is the climate variable of interest (temperature, precipitation, sunshine hours, or all of them); \( \beta \) is the associated coefficient estimated in equation (1); and \( \Delta ncP \) is the non-climate-influenced production, which is defined as

\[ \Delta ncP_{i,1980} = P_{i,1980} - \beta(C_{i,1980}), \]  

(5)

where \( P_{i,1980} \) is the actual production of rice in 1980 for county \( i \).

We then used the new predicted production and equation (2) to calculate rice centroid movement. This calculation 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.

Results

Factors contributing to rice production change
Almost all the parameters for the regression estimate were statistically significant at the 5% level or below (table 1). Regional specialization, e.g. GDP, fertilizer, irrigation, pesticide, and labor, is positively correlated with rice production in NEC. We found a positive effect for temperature and sunshine on rice production, which were highly significant (\( P < 0.001 \) and \( P < 0.05 \), respectively). As the units of production and factors are in log terms, a coefficient of 0.728 indicates that each 1% additional RAT improves rice production by 0.728%. We found no significant relationships between rice production and precipitation, as rice in NEC is all irrigated, which would compensate for rainfall deficiencies.

Urbanization has a negative effect on rice production (each 1% increase in urbanization decreased rice production by almost 0.05%). The negative effect may relate to decreasing rice cultivation and increasing use of paddy fields for vegetable production in suburban areas. The regional dummies are statistically significant. The institutional dummy between 1980 and 1989 had a positive sign, meaning the policy reform
during this period contributed to rice production growth, while it was not significant. On the other hand, the change in agricultural policy or market demand between 2000 and 2010 had a positive impact on rice production that was measurable at the 1% level of statistical significance.

From the growth account in table 2, it shows that rice production in NEC increased fivefold from 1980 to 2010. Table 2 suggests that 79.6% of this production growth came from the increased use of physical inputs. An average increase of 6.1% in RAT improved rice production by 4.4% (equal to a relative contribution of 0.87%), while the relative contribution from rainfall was negligible (0.01%). However, solar radiation had a negative contribution of approximately 0.2% due to its reduction over the past three decades. The total contribution of climate, 0.7%, is relatively smaller than that of physical input.

**Relocation of rice production centroid**

The spatial distribution of rice production also varied considerably over the three decades. Figure 2 shows the movements of the rice geographical centroid since 1980. By 2010, the centroid of rice production in NEC had moved 320 km northeastward (latitude 2.43 °N, longitude 1.80 °E) from Liaoning Province into Jilin Province. Rice relocation shifted most dramatically in the 1980s and 1990s, after the Household Responsibility System in the 1980s and when the New Development in Agricultural Policy started in the mid-1990s. Since 2000, rice production has continued to expand significantly in NEC and has now moved as far north into the northern part of Heilongjiang Province due to higher temperatures and market demand.

**Climate impact on relocation of rice production centroid**

The impact of climate factors on the relocation of the rice centroid is shown in figure 3. The four panels show the predicted movement of the rice production centroid if the only variable that changed from the 1980 level was RAT (panel B), GSP (panel C), GSS (panel D), or the combination of these three climate variables (panel A). Each panel demonstrates the historical movement of rice production for comparison. When combining all climate variables, the geographical centroid of rice production shows a clear west-to-east movement and a minor south-to-north pattern (figure 3, panel A). Figure S1 (see SI) also demonstrates that although there seems to be little coherency in the trend arising from precipitation and sunshine, the influence of temperature has a clear northeastward influence on the relocation of rice production.

**Discussion**

The introduction of cold-resistant rice in NEC in the early 1980s resulted in a significant increase in rice production. However, there is an increasing amount of evidence demonstrating stagnation in rice yield.
According to the National Bureau of Statistics of China, the entire regional increase was approximately 2.4 million ha of rice area between 1980 and 2010, while rice yield increased from 5.0 to 7.5 t/ha. The major driving factors of such dramatic growth are increasing market demand, physical inputs, and improved agricultural technology and management (You et al. 2009). However, the changes in climatic conditions during the past few decades have also had measurable, positive effects on the rice planting area and production in NEC. Our previous study showed that each 1% increase in the growing season temperature increased the rice planting area by nearly 3% in China during 1980–2010 (Li et al. 2015), especially in the northern parts of NEC, where the increase in temperatures has meant that the area has become suitable for rice planting (Piao et al. 2010, Gao and Liu 2011, Yang et al. 2011). For instance, a significant expansion in the rice planting area can be observed between 1980 and 2010 in NEC (see SI figure S1(A)), with a northeasterward shift in the rice area centroid from approximately 43°N to approximately 45°N (see SI figure S1(B)). Here, we estimate that the increase in RAT from 1980 to 2010 may increase rice production by 4.4%, but declining solar radiation reduced rice production by 0.9%. However, under the influence of climate change, the northern expansion of rice production may expose rice areas to relatively larger climatic variability in northern China. For example, an extreme cold event occurred locally in 2010 and caused rice losses in the Harbin area (Sun et al 2015). Climate change may also increase the frequency of extreme weather events and make them more damaging to rice production. Therefore, further adaptation measures to mitigate the impacts of weather and climate extremes will become more important in the future. For example, the development of new rice varieties that can grow within wider temperature ranges should be encouraged because it would help improve the ability of the rice to cope with extreme weather events.

In this paper, we attempted to distinguish the impacts of climate and non-climate factors on rice production growth and found that a 1% increase in rice RAT significantly increases production by 0.728%. The increasing RAT over the past three decades increased rice production by 4.4%, but declining solar radiation reduced rice production by 0.9%. However, under the influence of climate change, the northern expansion of rice production may expose rice areas to relatively larger climatic variability in northern China. For example, an extreme cold event occurred locally in 2010 and caused rice losses in the Harbin area (Sun et al 2015). Climate change may also increase the frequency of extreme weather events and make them more damaging to rice production. Therefore, further adaptation measures to mitigate the impacts of weather and climate extremes will become more important in the future. For example, the development of new rice varieties that can grow within wider temperature ranges should be encouraged because it would help improve the ability of the rice to cope with extreme weather events.

With so much uncertainty about the potential impacts of climate change, it is essential to evaluate what and how past climate changes have affected rice production. We have quantified the centroid movement of rice production in NEC over the past three decades and further evaluated the driving factors behind such movement. An impact analysis was developed to quantify how biophysical, socioeconomic, and technological factors influenced rice production change. Climate change had a significant effect on the relocation and expansion of rice production. In particular, we found that temperature had a clear

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**Figure 2.** Historical trends and centroid movements for rice production in Northeast China between 1980 and 2010. (A) Historical changes in rice production and (B) rice production centroid movements (different colored dots represent each decade).
northeastward influence on the relocation of rice production. However, the influence of precipitation was less spatially coherent because irrigation compensates for rainfall deficiencies. This was expected, as rice in NEC is almost always irrigated and was further confirmed by the significant and clear impact of irrigation on the geographical centroid of rice production (Li et al. 2015).

Our study demonstrates a process for synthesizing climate and crop-specific management and input data that can then be used to investigate the impact of climate change on crop production. Self-sufficiency in grain production remains the top priority for Chinese agriculture. This goal faces daunting challenges under the significant impact of climate change and rapid socioeconomic development. Understanding the historic evolution of rice and other crop production systems is critical for both estimating the economic impacts of future climate change and designing adaptation strategies to address future climate change.

**Conclusion**

Long-term data on crop, socioeconomic factors and climate provide us with the unique opportunity to

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*Figure 3. Predicted movements for the rice production centroids in Northeast China, which have a ln(y)–ln(x) relationship. (A) Changes due to all the climate factors combined; (B) changes due to RAT alone; (C) changes due to GSP alone; and (D) changes due to GSS alone. (Yellow dot: 1980–1990; orange dot: 1991–2000; red dot: 2001–2010; and the blue dots are the same as those from figure 2.)*
investigate their relationships more precisely and in terms of adaptation. During 1980–2010, rice production significantly increased and expanded northeastward. The majority of rice production growth came from increased agricultural inputs in the past three decades. The positive impacts of an increase in RAT played a significant and dominant role in determining the overall climate impacts on rice production and the coherent influence of moving the geographic centroid of rice production. However, the impact of GSP was not significant, while GSS had a significant but less spatially coherent influence. Our findings highlight the relationship between rice production systems and external driving factors, both climate and socioeconomics, and provide important insights into the adaptation of rice cropping systems in mid-high-latitude regions for the future.

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