Climate change and geographic shifts in rice production in China

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Abstract
Climate change can affect crop yield in a given location, and it can also affect where crops are grown. Most assessments of the effect of historical climate change on crop yield has been at the national level, ignoring possibly important subnational variation and climate change adaptation through changes in crop distribution. We analyzed the relationship between growing season temperature, rice yield, and the spatial distribution of rice production in China between 1949 and 2015. Since 1949, rice production in China has moved northwards. Because of this, country level average temperature for rice areas during the growing season was relatively stable, and colder than it would have been without the movement. Temperature has had a very small effect on rice yield at the country level of \(-0.05\ t\ ha^{-1} °C^{-1}\). However, this masks important subnational variation. Increased temperatures were associated with an increase in rice yield (0–1.0 t ha\(^{-1}\ °C^{-1}\)) in northern provinces and a decrease (\(-0.6–0\ t\ ha^{-1}\ °C^{-1}\)) in southern provinces of China. While the estimated overall effect of the northward movement on average rice yield in China was only 162 kg ha\(^{-1}\), it does illustrate how crop movements can modify climate change effects and can be an emergent adaptation strategy.

1. Introduction
There has been a considerable effort to understand the effect of recent climate change on crop yield (Lobell and Field 2007, Schlenker and Roberts 2009, Lobell et al 2011, Xiong et al 2014) as well as to project the effect of future climate change (Tao et al 2003, Parry et al 2004, Rosenzweig et al 2014). A difficulty in understanding and projecting climate change effects on crop yield is that agriculture is always adapting to environmental and social conditions through changes in crops, cultivars, planting dates, and other measures (Hijmans 2003, Olesen et al 2011, Kates et al 2012, Challinor et al 2014, Zhang et al 2015, Burke and Emerick 2016). An important factor that has been overlooked in most studies of the effect of climate change on crop yield is the role of changes in the geographic distribution of a crop through time. Such changes may occur in response to climate change or can happen for other reasons, and they could offset or add to national level climate change effects on yield. Possible future climate change driven changes in the spatial distribution of crops have been modeled (Leemans and Solomon 1993, Hannah et al 2013, Shabani and Kotey 2016), but there has been little research on historical changes in crop distribution and climate and how these interact to affect crop yield (e.g. Leng and Huang 2017, Qiao et al 2018).

A better understanding of the historical changes in the relation between climate, crop distributions, and yield could also help and improve assessments of future climate change effects and adaptation strategies for crop production. Here we explore how these factors have interacted in rice production in China. In this study, we analyze changes in the spatial distribution and yield of the rice crop in China in relation to climate change, using province-level data for a 67-year period (1949–2015). As almost all rice production in China is irrigated (Peng et al 2009), we do not consider the effect of variation in precipitation. We describe spatial variation and trends in rice area and yield, and in the growing season temperature in China, and we use regression to estimate the effect
of temperature on detrended yield. We also address the question whether changes in the geographic distribution of rice area modified the national level effect of climate change on yield.

2. Materials and methods

2.1. Data sources

Province level rice area and yield for 1949–2015 were obtained from the survey data of the National Bureau of Statistics of China (http://data.stats.gov.cn/). Twenty-nine Chinese provinces were included in this study (figure 1). Xizang (Tibet) and Qinghai provinces were omitted for having about 1 ha of rice or less in most years. To create a consistent time series, data from newly formed provinces were combined with the provinces they split from. That is, Chongqing was merged with Sichuan, and Hainan was merged with Guangdong. Land area of each province in China from MCA (2012) was used to calculate the percent of rice area for each province in China. Time series of monthly gridded minimum and maximum temperature data during 1949–2013 for the rice growing areas in each province of China were extracted from the CRU TS3.10 dataset (Harris et al 2014). Rice planting and harvesting dates from the spatial database of rice calendars (Laborte et al 2017) for China were used to determine the rice growing season and cropping system. Generally, for single cropping rice systems, the growing season is from May to September. For double cropping rice systems, the first season is from April to July, and the second season is from July to November. Fujian, Guangxi, Hunan, Jiangxi, Zhejiang and Guangdong were considered as areas with double cropping of rice. The other provinces have a single rice cropping system.

2.2. Statistical analysis

Changes over time in rice area, yield (from 1949 to 2015), and mean rice growing season temperature (from 1949 to 2013) in each province were investigated with linear regression models: \( Y_{i,t} = b_i + a_i \times \text{year} \), where \( Y_{i,t} \) is the yield (or rice area or mean temperature) in province \( i \) in year \( t \). Intercept \( b_i \) is a province fixed effect, and slope \( a_i \) is the province-specific time effect.

The residuals of the linear regression model between rice yield and time were used to investigate the effect of temperature on yield (from 1949 to 2013). The residuals were used to remove the effect of the trend of increasing yields due to changes in crop management, such as increased fertilizer use and varietal change. The residuals (hereinafter referred to as ‘detrended yield’) were regressed with the average growing season temperature for its corresponding year to evaluate the effects of cold and warm years on rice yield for each province, and the entire country: \( Y_{i,t} - (b_i + a_i \times \text{year}) = d_i + c_i \times T_{i,t} \), where \( T_{i,t} \) is the mean temperature in province \( i \) in year \( t \), \( d_i \) is a province fixed effect, and \( c_i \) is the temperature effect.

To disentangle the effect of changes in temperature and of geographic shifts of rice area, we considered the amount of climate change observed as an effect of one factor by keeping the other constant. Province level rice area and temperature data (for two ‘time spans’: annual mean temperature and average temperature during rice
3. Results

3.1. Country level trends in rice production, area, and yield

Rice production in China more than quadrupled between 1949 and 2015 (figure 2(a)). With the rice area relatively stable at about 31 million ha (figure 2(b)), these production gains mostly resulted from the increased grain yield (production/area). Rice area peaked in 1976 at 36 million ha and declined to 27 million ha in 2003. Since 2004, rice area has slowly increased again and reached 30 million ha in 2010s (figure 2(b)). Grain yields increased from 1.9 t ha\(^{-1}\) in 1949 to 6.9 t ha\(^{-1}\) in 2015 (figure 2(c)) as a result of the use of new varieties and intensification, such as the increased use of fertilizer (Peng et al 2009). Rice yield was reported to be stagnating, or even to be declining after 1998 (Peng et al 2009, Ray et al 2012), but this now appears to have been a short-term deviation and since 2003, rice yield has increased by 62 kg ha\(^{-1}\) year\(^{-1}\) (figure 2(c)).

3.2. Changes in geographic distribution of rice in China from 1949 to 2015

Since 1949, there have been considerable changes in the spatial distribution of rice in China (figures 3(a), (b) and table S1 is available online at stacks.iop.org/ERC/1/011008/mmedia). In 1949, ten southern provinces (Anhui, Fujian, Guangdong, Guangxi, Hubei, Hunan, Jiangsu, Jiangxi, Sichuan and Zhejiang) had 23 million ha in total, with 4.7 million ha in Guangdong alone. By 1980, total rice area in these provinces had increased by 30% to 30 million ha (while the national area was 34 million ha), even though rice yield decreased by 11% (19,848 ha year\(^{-1}\)) in Guangdong and 10% (4,831 ha year\(^{-1}\)) in Sichuan; as the rice area increased by 40 to 90% in the southern provinces Anhui, Guangxi, Hubei and Hunan, Jiangsu, Jiangxi and Zhejiang. This trend of increasing rice area in southern China reversed after 1980 and by 2015. Rice area in these ten southern provinces had declined by 24% relative to 1980, to 23 million ha; that is, very similar to what it was in 1949. The southern provinces that lost most rice area during this period were Guangdong 47% (60,122 ha year\(^{-1}\)) and Zhejiang 67% (61,464 ha year\(^{-1}\)).
While rice area increased in southern China between 1949 and 1979, the rice area in other provinces was relatively stable. In contrast, while the rice area decreased in southern China after 1980, there was a strong increase of rice area in northern China. Rice area planted in Heilongjiang province was 0.21 million ha in 1980 and increased more than 14-fold to 3.1 million ha in 2015 (89,377 ha year$^{-1}$). Thus, while the national rice area during past 67 years was relatively stable for China, there were first rice area gains, and then area losses in the South, as well as a rapid expansion in the North (Heilongjiang province in particular) after 1980.

### 3.3. Changes in rice yield in China from 1949 to 2015

Rice yields are currently highest in central and northern provinces of China (figure 3(c)). Henan, Hubei, Jiangsu, Jilin, Liaoning, Ningxia, Shandong, Shanghai and Xinjiang currently have rice yields of 8 t ha$^{-1}$ or more. The highest yield increases were observed in central and north China (figure 3(d)). Since 1980s, Gansu, Heilongjiang, Nei Mongol, Shandong, Shanghai and Xinjiang had yield increases of over 100 kg ha$^{-1}$ year$^{-1}$. Yield increases in Gansu, Heilongjiang, Henan, Hubei, Jiangsu, Jilin, Liaoning, Nei Mongol, Ningxia, Shandong, Shanghai, Sichuan and Xinjiang (89–132 kg ha$^{-1}$ year$^{-1}$) were much higher than the country-level average yield increase (84 kg ha$^{-1}$ year$^{-1}$) during the past 67 years.
3.4. Rice growing season temperature in China from 1949 to 2013

During the study period of 1949–2013, the mean temperature during the rice growing season in southern China was about 20 °C–25 °C, whereas it was around 16 °C–20 °C in northern China (figure 4(a)). There was difference in the trends of mean temperature between 1949–1979 and 1980–2013 (figure 4(b)). From 1949 to 1979, most provinces experienced cooling of 0 °C–0.3 °C decade−1. However, from 1980 to 2013, there was warming of about 0 °C–0.5 °C decade−1 in most provinces. Overall from 1949 to 2013, warming was observed for all provinces by 0 °C–0.2 °C decade−1. Warming was slightly stronger in the north than in the south during the rice growing season.

3.5. Effect of temperature on yield

At the country level, the estimated effect of temperature on yield (−0.05 t ha−1 °C−1) was very small during 1949–2013. However, in northern China, detrended rice yield generally was higher in warm years, while in southern China, rice yield was lower in warm years (figure 5). In provinces Gansu, Nei Mongol, Heilongjiang and Jilin, yield increased with more than 0.3 t ha−1 for a positive temperature anomaly of 1 °C. In contrast, rice yields were lower in years with high temperature in the central and southern provinces. A temperature anomaly of 1 °C was associated with a yield decline of 0.6 t ha−1 in Shanxi, and 0.2 t ha−1 in Sichuan, Hebei, Henan and Anhui.

3.6. Temperature changes related to area

The annual average temperature of the rice area in China decreased between 1949 and 2013 (figure 6(a)). In 1949–1970, average mean temperature in rice planting areas declined from 18 to 17 °C. It continued to slowly decline after that until 2005, after which it declined sharply to 15 °C. If the spatial distribution of rice growing area had not changed since early 1950s, the average annual temperature in rice growing areas would have been

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Figure 4. Mean temperature of the rice growing season (a) and temporal trend in temperature (b) for major rice producing provinces in China during three time periods (1949–1979, 1980–2013 and 1949–2013).

Figure 5. Effect of temperature on rice yield for Chinese provinces (1949–2013). The effect is the slope coefficient of a linear regression model between detrended yield and growing season temperature.
2.4 °C higher than what it actually was by 2013. If the temperature had not changed since the early 1950s, with the effect of the movement of the rice area, the average temperature would have declined from 18 to 15 °C.

The trend in average temperature during the rice growing season in rice planting areas in China was similar as the trend in annual average temperature, but with more variability and much less overall change (figure 6(b)). Actual mean temperature declined from 23 to 22 °C during 1949–1970, then it stabilized around 22.5 °C between 1970 and 1990. After 1990, it increased back to 23 °C followed by a decrease. If rice area had not changed since the early 1950s, the rice area temperature would have been about 0.7 °C higher by 2013. In the absence of climate change since the early 1950s, the changes in rice planting area would have decreased the rice area temperature by 0.7 °C.

3.7. Yield changes related to area
If the spatial distribution of rice area at the province level had not changed since the 1980s, estimated country level average rice yield, based on the observed province level yields, would have been 91 kg ha$^{-1}$ lower on average in the most recent five years in this study (2011–2015). If the spatial distribution of rice area had not changed after 1949–1951, country level rice yield would have been 162 kg ha$^{-1}$ lower than the actual yield in 2011–2015 (figure 7).

4. Discussion and conclusion

From 1980 to 2015, rice area decreased in southern China. This was during an era of moderate warming in the south. We found a very weak negative effect of high temperature on rice yield in the south, and the reduction in rice area in this region is likely not directly linked with warming. During this period of strong economic development labor has left agriculture, and demand for more high value agricultural products such as vegetables soared (Wang et al 2014). In many cases, double cropping of rice was replaced with a single crop of rice (Chen et al 2013, You et al 2011).

Despite the reduction of rice area in southern China during this period, national level rice area was relatively stable, because rice area increased in northeast China since 1980s. The warming climate extended the growing season, and such facilitated the expansion of rice there (Gao and Liu 2011). This is supported by our finding that
rice yields in the north are higher in warmer years, which was also reported by Chen et al. (2014). The northwards expansion of rice was therefore likely supported by warming (Hijmans 2007, You et al. 2011). However, the increase in rice area in northern China cannot be simply ascribed to climate change alone. The north specializes in production of the temperate japonica rice varieties for which there is now more demand (Feng et al. 2017).

Changes in the geographic distribution of rice area in China were reported before (Hijmans 2007, You et al. 2011, Liu et al. 2013, Dong et al. 2016), but we studied it over a longer period (from 1949 to 2015) than these other studies that did not consider data before the 1980s and we focused specifically on yield and on climate change effects.

Rice yield was reported to have stagnated after 1998 (Peng et al. 2009). This stagnation was ascribed to declines in soil fertility (Tong et al. 2003), global warming (negative impacts on rice yield in south China) and technology limitations (e.g. less developed irrigation practices in southwestern China) (Zhang et al. 2014). Van Wart et al. (2013) suggested that rice yield in China has approached its biological yield potential. However, it now appears that the stagnation was temporary as yield has been increasing again, albeit at a lower rate than prior to 1998.

Due to the northward change in the geographic distribution of rice in China, the average rice growing season temperature was lower than it would have been without geographic shifts. At the national level, we found no clear effect of high temperature on yield. More importantly, national level effects can be misleading if the underlying geographic distribution of the crop changes (Leng and Huang 2017). In China, the effect of high temperature was negative in the south and positive in the north.

Our results about the relationship between rice area and yield suggest that the movement of rice production to the northeast China has increased country-level rice yield slightly. It indicates that a small fraction of the yield increase over the past decade is due to a shift of rice planting to the higher-yield regions in the northeast. The overall change in yield due to the change in location is equivalent to about one year in yield increase due to technological change, and thus not very important. However, the change in rice area has made a larger contribution to the change in rice yield than climate change. Also, the high yield gap found in northeast China due to the high yield potential enables by climate change effects may imply a further improvement of the rice yield and total production in China (Zhang and Yang 2016). And as climate continues to warm, the ‘pull’ from the north may become matched with a ‘push’ from the south.

Despite the small effects of high temperatures and of geographic movement on rice yield in China, it is clear that changes in the geographic distribution of a crop can modify the effect of climate change on crop production. This is an important factor to be considered when investigating past and future climate change impacts on crop production and adaptation.

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