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Northward expansion of paddy rice in northeastern Asia during 2000–2014

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Abstract

Paddy rice in monsoon Asia plays an important role in global food security and climate change. Here we documented annual dynamics of paddy rice areas in the northern frontier of Asia, including northeastern (NE) China, North Korea, South Korea, and Japan, from 2000 to 2014 through analysis of satellite images. The paddy rice area has increased by 120% (2.5 to 5.5 million ha) in NE China, in comparison to a decrease in South Korea and Japan, and the paddy rice centroid shifted northward from 41.16°N to 43.70°N (~310 km) in this period. Market, technology, policy, and climate together drove the rice expansion in NE China. The increased use of greenhouse nurseries, improved rice cultivars, agricultural subsidy policy, and a rising rice price generally promoted northward paddy rice expansion. The potential effects of large rice expansion on climate change and ecosystem services should be paid more attention to in the future.

1 Introduction

Paddy rice agriculture provides staple grain for almost half of the global population [*Elert*, 2014] and also substantially affects water use [*Kuenzer and Knauer*, 2013; *Samad et al.*, 1992], zoonotic infectious disease transmission [*Gilbert et al.*, 2008, 2014], and climate change [*Chen et al.*, 2013; *Ehhalt et al.*, 2001; *Sass and Cicerone*, 2002; *van Groenigen et al.*, 2013]. Asia produces more than 90% of the world's rice grains [*Kuenzer and Knauer*, 2013] with the largest paddy rice planting area [*Maclean and Hettel*, 2002] of any continent. In the past few decades, industrialization and urbanization have resulted in substantial losses of high-quality croplands in southern China [*Liu et al.*, 2010]. In order to compensate the loss of croplands over the years and to meet increasing demands on both rice production [*Elert*, 2014] and rice quality (e.g., Japonica rice) due to growing population and changing diets, paddy rice agriculture has been expanding northward into cold regions in northeastern (NE) China, for example, the

Sanjiang Plain in Heilongjiang Province [*Liu et al.*, 2004; *Wang et al.*, 2011; *Yang et al.*, 2007; *Zhang et al.*, 2009].

Over the past decade, a lot of attention has been given to track the dynamics of paddy rice area in South Asia, Southeast Asia, and southern China [*Bridhikitti and Overcamp*, 2012; *Gumma et al.*, 2011, 2014; *Xiao et al.*, 2006, 2005], where the loss of paddy rice fields occurred extensively. The recent rapid expansion of paddy rice into the cold regions of NE Asia has until now been largely overlooked [*Shi et al.*, 2013]. There has been no accurate picture on annual dynamics of paddy rice areas in NE China and three neighboring countries (North Korea, South Korea, and Japan) in this temperate climate zone (Figure S1 in the supporting information). In addition, our understanding about the drivers of rice agriculture dynamics was still incomplete. The rice area expansion in NE China was found to coincide with the increasing annual temperature from 1958 to 2000, which suggested that climate change, often represented by warming, may be driving paddy rice expansion [*Gao and Liu*, 2011]. Japan, South Korea, and North Korea also showed varied trends of paddy rice changes with differing drivers among them [*Hong et al.*, 2012; *Organisation for Economic Co-operation and Development* (*OECD)*, 2008; *Yoon*, 2006]. However, these existing reports are spatially and temporally scattered, and a cross-country comparative analysis in NE Asia has not yet been conducted. The lack of such accurate information clearly hinders cross-country comparison and accurate assessment of ecological and social effects from the northward expansion of paddy rice. In addition, common natural and socioeconomic drivers for the dynamics of paddy rice areas across these countries are not well identified.

Rapid paddy rice expansion in the cold region did ensure food security, but it also raises environmental issues such as increased use of agrochemicals [*Tao et al.*, 2008], water insecurity [*Tao et al.*, 2008], enhanced methane emission [*Chen et al.*, 2013; *Zhang et al.*, 2011], and losses of wetlands [*Song et al.*, 2012; *Zhang et al.*, 2009] and biodiversity [*Bobbink*, 2008; *Zhu et al.*, 2000]. Therefore, quantifying paddy rice expansion and its drivers in the 21st century in NE Asia, especially in NE China, is necessary for better assessing food security and the environmental impacts from agricultural expansion, which would contribute to sustainable agricultural development, balancing ecological service, and human well-being [*Foley et al.*, 2005].

By developing unprecedented annual paddy rice maps for NE Asia from Moderate-Resolution Imaging Spectroradiometer (MODIS) optical and thermal data and a phenology-based paddy rice mapping algorithm [*Xiao et al.*, 2006, 2005; *Zhang et al.*, 2015], we examined the spatiotemporal dynamics of paddy rice planting areas in NE Asia from 2000 to 2014, where high-quality rice feeds billions of people throughout the world. We also explored climatic and socioeconomic factors that might drive annual dynamics of paddy rice agriculture including climate warming, policy, price, and technology, as well as the potential climate feedbacks responding to the rapid rice expansion.

2 Materials and Methods

2.1 Image Data

Optical and thermal data from the MODIS sensor from 2000 to 2014 were used, specifically the 8 day composite surface reflectance product (MOD09A1, 500 m resolution) from Terra satellite [*Vermote and Vermeulen*, 1999] and the land surface temperature (LST) data (MYD11A2, 1 km resolution) from Aqua satellite. Quality flags such as clouds and cloud shadows were used to exclude bad observations, and gap-filling of time series spectral index and LST data was conducted via the linear interpolation approach [*Xiao et al.*, 2006, 2005; *Zhang et al.*, 2015], and 1 km LST data were resampled into 500 m to match the MOD09A1 data sets. We used the Aqua-derived MYD11A2 data instead of the Terra-derived MOD11A2 data as the observations at ~01:30 A.M. from Aqua yield a lower temperature closer to the minimum daily temperature, which is the major limiting temperature indicator for crops in cold regions.

2.2 Data on Natural and Socioeconomic Factors

The Shuttle Radar Topographic Mission digital elevation data (DEM) and climate zone data [*Peel et al.*, 2007] were acquired for the spatial analysis of paddy rice expansion as the altitude and climate gradients. Air temperature, rice price, and agricultural technology indicators were collected for the driver analysis. Specifically, air temperature data during 1981–2013 from the University of East Anglia Climatic Research Unit time series 3.2 data sets (0.5° × 0.5° resolution) [*Harris et al.*, 2014] were acquired for a long-term analysis of climate variation and change. The annual producer price indices data for rice were derived from the statistics division of the Food and Agriculture Organization of the United Nations (FAOSTAT) [*Food and Agriculture Organization of the United Nations*, 2014]. The greenhouse film consumption data, which reflect the use of agricultural technology (i.e., greenhouse nurseries), were acquired from the China Environmental Statistic Yearbook. In addition, population, rice production, and import data were also collected for the food security status analysis from the World Bank, FAOSTAT, or national statistics authorities. Rice cultivar information was collected from previous literatures.

2.3 Paddy Rice Mapping and Validation

The phenology-based paddy rice mapping method (namely, RICE-MODIS, driven by MODIS data) has been used for paddy rice mapping in tropical and subtropical regions [*Xiao et al.*, 2006, 2005]. An improved method, with inclusion of the LST-derived thermal plant growing season [*Zhang et al.*, 2015], was used to produce annual paddy rice maps in NE Asia (supporting information Texts S1 and S2 and Figures S2–S7). Accuracy assessment of the resultant paddy rice maps included three aspects (supporting information

Text S3 and Figures S8–S14): (1) validation of the 2014 paddy rice map (supporting information Table S1) by using very high resolution images in 2014 and field photos collected in the summer of 2013 and available in the Global Geo-Referenced Field Photo Library (http://eomf.ou.edu/photos/) [*Xiao et al.*, 2011]; (2) comparisons of the paddy rice maps with the existing land use maps (supporting information Figures S9 and S10); and (3) comparison of paddy rice maps with agricultural statistical reports (supporting information Figures S11 and S12).

2.4 Spatiotemporal Analysis of Paddy Rice Planting Area

The annual area of paddy rice from 2000 to 2014 was quantified first by country. The trajectory of paddy rice planting area centroid movement from 2000 to 2014 was also analyzed. We aggregated the 500 m binary paddy rice maps into fractional (%) rice maps within a 10×10 pixel window (~$5 \times 5\ km^2$ grid) and then calculated a map of paddy rice change rates from 2000 to 2014 by using the linear regression method. The distributions of change rate in different countries as well as across latitude and elevation gradients were analyzed to illustrate the geographical patterns of paddy rice expansion in NE Asia.

2.5 Analysis of Drivers of Paddy Rice Area Expansion

Through the field survey, literature review, and consultation with local experts, we found that there were four major drivers affecting paddy rice area dynamics including (1) climatic warming, (2) agricultural technology such as greenhouse nurseries and rice cultivar improvement, (3) agricultural policy, and (4) rice price. We used quantitative and qualitative approaches to determine the influences of these four drivers. The mean (minimum) air temperature during the growing season and early growing season was calculated as the average of monthly mean (minimum) temperature from April to October and from April to May, respectively. The temperature variations and trends in two periods (1981–2013 and 2000–2013) were analyzed for different countries. The relationships between paddy rice planting area dynamics, and the three factors (temperature, price, and greenhouse film consumption) were examined by using correlation analysis, while qualitative analysis was used to analyze the effects of national agricultural policies and rice cultivar improvements on paddy rice area changes.

3 Results and Discussion

3.1 Annual Dynamics of Paddy Rice Planting Area in NE Asia

We generated annual maps of paddy rice planting areas in NE Asia with a spatial resolution of 500 m for the years 2000 to 2014 through analysis of MODIS time series images and a phenology-based rice mapping algorithm (supporting information Texts S1 and S2 and Figures S2–S7). Despite the effects of potential mixed pixel problem, MODIS data supported the annual paddy rice mapping efforts with a reasonably high accuracy (supporting information Figures S9–S12). The paddy rice planting area in 2014 accounted for ~6% of the total land area in NE Asia, and approximately 90% of paddy rice was distributed in the alluvial plains with an average elevation less than 300 m. Paddy rice in NE China is mainly located in the northeastern (Sanjiang Plain), western (Songnen Plain), and southern plains (Liaohe Plain). Paddy rice in the Korean peninsula is mostly located in the western coastal plains with some located in the narrow valleys of central and southern mountainous areas in South Korea. In Japan, paddy rice fields are also distributed in the coastal alluvial plains in the islands (Figures 1 and S1 in the supporting information).

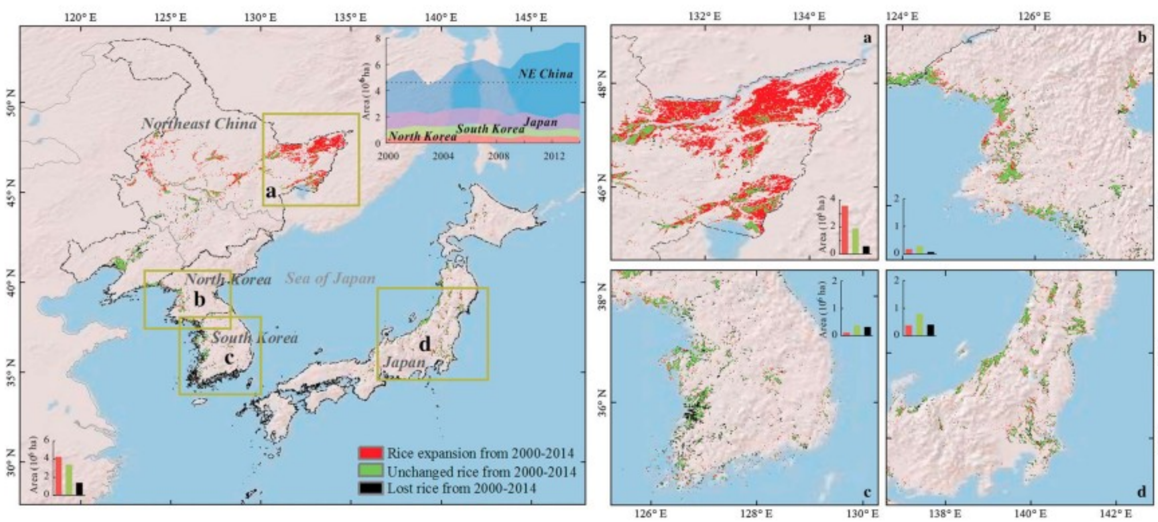

Figure 1. Spatial distribution of paddy rice area changes in northeastern (NE) Asia from 2000–2014. The zoom-in figures in the right side are for (a) NE China, (b) North Korea, (c) South Korea, and (d) Japan, corresponding to the box a–d in the main figure. The column graphs in the five figures show area distributions of three categories, including unchanged paddy rice, rice expansion, and lost paddy rice area from 2000 to 2014. The stacked area figure in the major map shows the interannual paddy rice area variations of the three countries and one region.

Paddy rice planting areas in NE Asia have increased by 60% from 4.77×10^6 ha in 2000 to 7.63×10^6 ha in 2014 (Figure 1). The annual dynamics of paddy rice planting areas differed substantially among NE China, North Korea, South Korea, and Japan. The rice expansion in NE Asia was generally attributed to the dramatic increase in NE China (104%), while the net change in the other three countries was negligible (North Korea 4%, South Korea −7%, and Japan −1%). Specifically, paddy rice planting area in NE China had a substantial increase of ~120% from 2.48×10^6 ha in 2000 to 5.46×10^6 ha in 2014. Over that same period, North Korea had a moderate increase of 27% from 0.37×10^6 ha to 0.48×10^6 ha, while South Korea had a moderate decrease of 29% from 0.71×10^6 ha to 0.50×10^6 ha. The paddy rice area in Japan decreased slightly over these 15 years, ranging from 1.21×10^6 ha in 2000 to 1.18×10^6 ha in 2014 (Figure 1). It is important to point out that the increased area (2.98×10^6 ha) of paddy rice in NE China over the period of 2000–2014 is 38% larger than the total paddy rice area in the other three countries in 2014 (2.16×10^6 ha).

3.2 Geographical Characteristics of Paddy Rice Expansion

We carried out a trajectory analysis to quantify latitudinal shifts in paddy rice in the region. The results showed that the paddy rice area centroid moved northward by 310 km (from 41.16 to 43.70°N) from 2000 to 2014 (Figure 2a). A significant increase in paddy rice area occurred in the high-latitude regions (44.0–47.5°N, supporting information Figure S15), which led to a northward shift of the national rice production centroid in China [*Liu et al.*, 2013].

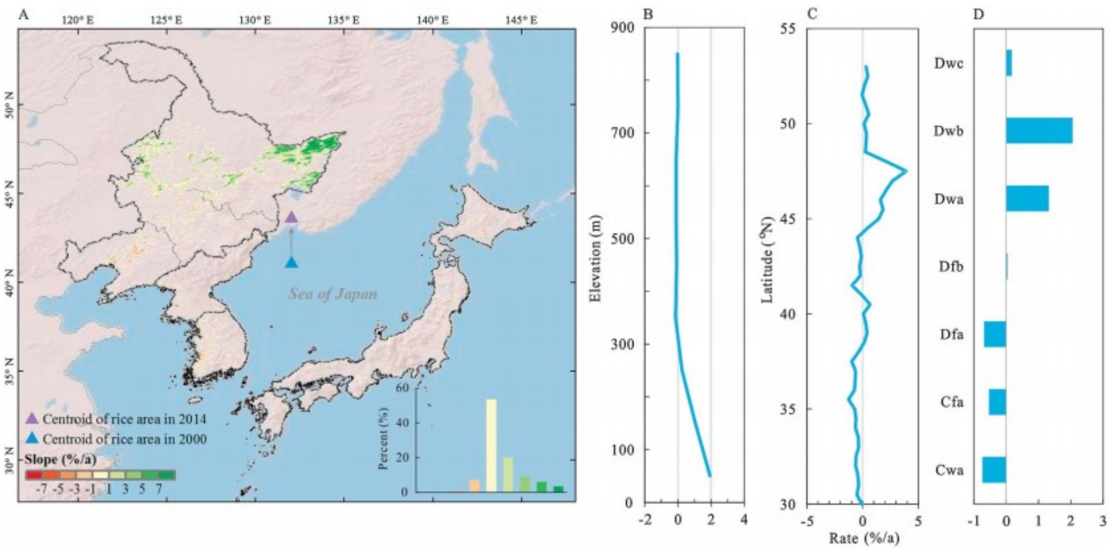

Figure 2. Geographical pattern of the paddy rice change rates. (a) Spatial distribution of the significant paddy rice trend ($p < 0.05$) at 5 km × 5 km grid cells. The inset shows the distribution of different paddy rice change rate levels in NE Asia. The trajectory of paddy rice centroid from 2000 to 2014 is shown in the map in Figure 2a. (b–d) The distribution of paddy rice change rates along different geographical factors: (Figure 2b) elevation gradients, (Figure 2c) latitude gradients, and (Figure 2d) climate zones (supporting information Figure S1).

We investigated where significant changes in paddy rice area took place in the region, based on the map of paddy rice change rates from 2000 to 2014 at ~5 km spatial resolution (Figure 2a, see section 2). The area with significant paddy rice area changes ($P < 0.05$ and $|r| > 1\%$) accounted for 46% of all the rice grid cells in NE Asia (Figure 2a), 41% of which occurred in NE China and ~5% in North Korea, South Korea, and Japan. Among those grid cells with significant paddy rice changes, approximately 83% of them had a positive expansion ($r > 1\%$) (Figure 2a). Significant paddy rice expansion occurred in NE China with ~81% of rice grid cells yielding an *r* of >1%, mainly in the Sanjiang and Songnen Plains, the northern most plains in China.

The characteristics of significant paddy rice expansion from horizontal (latitude) and vertical (elevation) dimensions were analyzed as well. The paddy rice expansion rates decreased as elevation increased in NE Asia, and 90% of the paddy rice expansion happened in those areas with elevation below 250 m above sea level (Figure 2b). Paddy rice expansion occurred in plain areas through conversion from either croplands or natural wetlands [*Song et al.*, 2014]. The relationship between paddy rice expansion and latitude showed that the largest proportion of paddy rice expansion was distributed in the area with a latitude range of 44.0–47.5°N (Figure 2c), primarily due to the rapid area increases in the Sanjiang Plain in NE China (Figure 2a).

We also examined the distribution of significant paddy rice expansion among different climate zones (Figures 2d and S1 in the supporting information). Paddy rice expansion was concentrated in the colder regions including Dwa climate (cold, dry winter, and hot summer) and Dwb climate (cold, dry winter, and warm summer), while paddy rice reduction occurred in warmer Cwa climate zone (temperate, dry winter, and hot summer) (see supporting information Figure S1 for a detailed description of climate zones). The results further indicate that paddy rice expanded into colder regions in NE Asia.

3.3 Drivers and Climatic Effects of Paddy Rice Expansion

Paddy rice farming is a complex system and driven by many natural and anthropogenic factors. As thermal conditions are the major constraint for cropping in cold regions, we investigated whether the improvement of biophysical (thermal) conditions, driven by climate warming and/or artificial warming (greenhouse nurseries technology), has promoted paddy rice expansion in NE Asia. The air temperatures during the whole growing season (April–October) and the early growing season (April–May) showed increasing trend in the past three decades (Figures 3a and S16–S18 in the supporting information) in NE China, but a turning point occurred around 2000. Previous studies reported that significant warming in the 1980s–1990s met the thermal requirement for rice planting [*Dong et al.*, 2009; *Gao and Liu*, 2011]. Past warming has resulted in satisfactory thermal conditions for rice cultivation in the region, while the recent reported warming hiatus during the growing season or reversal of the trend for the early growing season in 2000–2014 [*Li et al.*, 2015] did not prevent the expansion of paddy rice in high-latitude regions. The transplanting dates for Japan and South Korea are earlier than those for NE China (Figure S5), which implied that NE China at higher latitudes may suffer from more chilling hazards. Greenhouse nursery technology is an important approach to avoid chilling injury of rice. We used greenhouse film consumption as an indicator for application of greenhouse nursery technology, and the data show that there was a significant correlation between paddy rice area and the amount of greenhouse film consumption in 2000–2013 in NE China ($R^2 = 0.95$, $p < 0.001$, Figure 3b). The two images (Figure 3b) showcase an increasing use of rice nursery greenhouses in NE China. A literature review showed that new cultivars, especially an improved cold tolerance of Japonica rice cultivars (supporting information Table S2), are critical for improving the adaptability of rice agriculture in NE China [*Song et al.*, 2015; *Wei et al.*, 2008]. This suggests that improved rice cultivars and artificial warming efforts through greenhouse nursery technology play an important role in paddy rice expansion by enabling earlier rice seeding and safeguarding rice seedlings from freezing risks in early spring. Both natural (climate change) and artificial warming (greenhouse nursery) as well as improved cold tolerance of new rice cultivars have acted together to meet the thermal requirement for paddy rice cultivation in NE China in the past few decades.

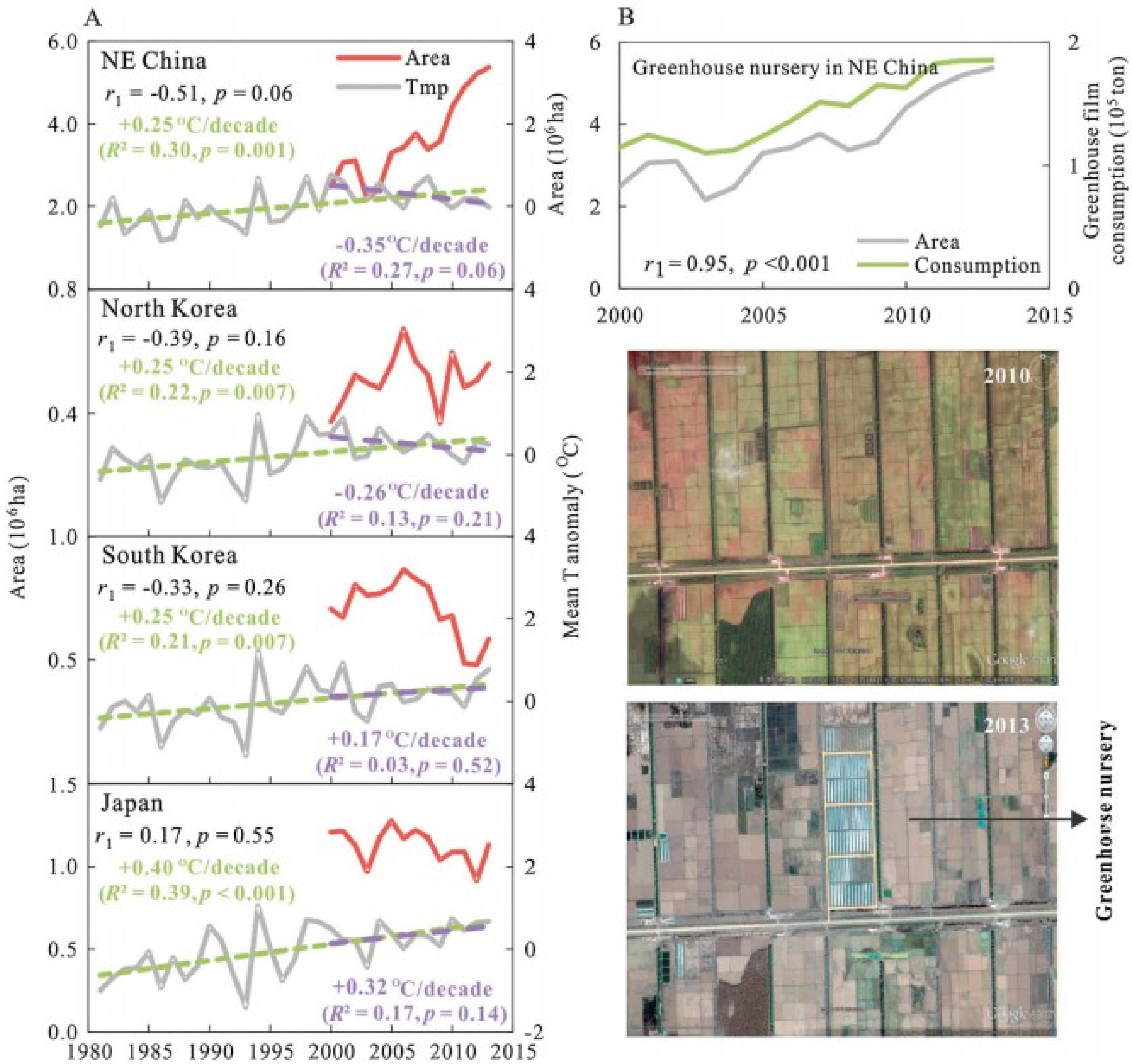

Figure 3. Climatic and artificial warming effects on paddy rice changes. (a) The interannual variations of the growing season (April–October) mean air temperature from 1981 to 2013 for NE China, North Korea, South Korea, and Japan. The trends for two time periods (1981–2013 in green color and 2000–2013 in violet color) are also shown in the figures. The correlation coefficient (*r* and *p*) between paddy rice area and temperature were shown in black text. (b) The interannual variation of greenhouse film consumption in NE China from 2000 to 2013. Greenhouse film consumption is considered as an indicator of the greenhouse nursery technology in NE China. The two snapshots below showcase the rapid expansion of nursery greenhouses in NE China with high resolution images derived from Google Earth.

We investigated the potential impacts of agricultural policy on paddy rice expansion in NE China. In 2004, Chinese national government dropped a multidecade agricultural tax policy that collected tax from farmers and started to implement a new nationwide agricultural subsidy policy [*Huang et al.*, 2013]. The rice expansion rate after 2004 was higher than that before 2004 (Figure 4a), which may be attributed to the incentives of the policy. Previous studies also indicated that the agricultural subsidy policy promoted the agricultural expansion and reclamation of previously abandoned croplands [*Song et al.*, 2014].

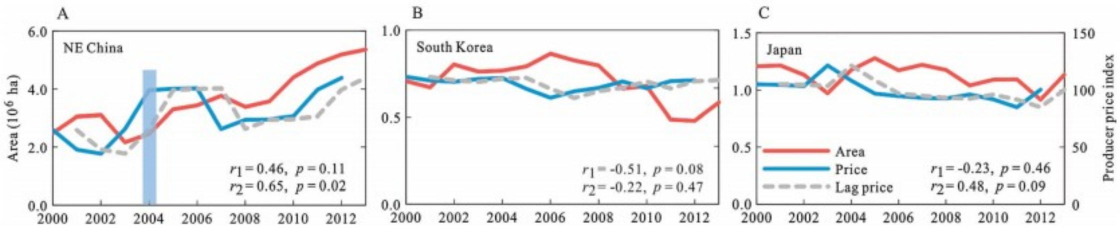

Figure 4. Interannual variations of paddy rice area and price. Annual producer price indices of paddy rice (from 2000 to 2012) and paddy rice area (from 2000 to 2014) in (a) NE China, (b) South Korea, and (c) Japan. North Korea is not included due to the unavailability of price data. Dotted line shows the 1 year lag of price data. The year of agricultural subsidy policy implement in China (2004) is marked in Figure 4a.

We further investigated the role of agricultural economy on paddy rice expansion in NE Asia. Annual data of sale price of rice grains over years for individual countries were collected and analyzed in relation to annual dynamics of paddy rice area. In NE China, the correlation between rice sale prices and paddy rice areas with a 1 year lag is statistically significant ($p < 0.05$), and the price explains ~42% of the observed changes in paddy rice areas in NE China ($r = 0.65$, $p = 0.02$, Figure 4a). This suggests that farmers' decisions to pursue paddy rice planting were partly motivated by the market price of rice. The rice price drop in 2002 was followed by a large decrease of paddy rice area in 2003 [*Shi et al.*, 2013]; the price drop in 2007 was also consistent with the decrease of paddy rice area in 2008 (Figure 4a). In Japan, rice grain sale price explains 25% of the annual variation of paddy rice area ($r = 0.48$, $p = 0.09$, Figure 4c). In contrast, there was no significant relationship between paddy rice areas and rice prices in South Korea (Figure 4b). This seems to be a result of active and strong agropolicy of market price support by South Korean governments to sustain rice farming and production [*OECD*, 2008], which leads farmers to be less dependent on market price for their decision making (supporting information Figure S19c).

Quantifying relative contributions of the biophysical (climate components such as temperature) and anthropogenic (technology, policy, and economy) driving factors on land use changes is always a big challenge as many factors are interrelated. Understanding the effects of climatic change, in particular of warming, on rice expansion requires considering the warming trend during the past decades prior to the study period (2000–2014). Although this study did not quantify the relative contributions of individual drivers (climate, technology, policy, and economy), we can qualitatively conclude that when the biophysical conditions met most of thermal requirements for paddy rice cultivation, use of agricultural technology such as greenhouse nurseries and improved rice cultivars furthermore guards paddy rice cultivation in the colder regions of NE Asia. Favorable agricultural policy (e.g., no agricultural tax) and the rising sale price of rice grain would further encourage broad use and investment in agricultural technology for paddy rice production. All of these four factors have been working together to drive rapid expansion of paddy rice in NE China.

It is interesting to note that while the warming trend during the whole growing season over 2000–2014 showed weakening in NE China and North Korea, it remained the same in South Korea and Japan (Figure 3a), which was consistent with the paddy rice change trends in these four countries/regions. This suggests that paddy rice agriculture could be one critical driving factor for local climate variability and change. We speculate that expanded paddy rice agriculture could have contributed to the cooling in NE China and North Korea due to the evaporative cooling mechanism that increases water content in the atmosphere through evapotranspiration. However, additional studies are needed to consider more factors, including but not limited to other land cover changes (e.g., afforestation in NE China) and changes in cloud cover, atmospheric circulation, and snow cover.

4 Conclusions

This study represents the first effort to document interannual variations of paddy rice in NE Asia, a new frontier for paddy rice expansion in the 21st century. Specifically, this study provided satellite-based evidence for a remarkable northward expansion of paddy rice from 2000 to 2014, largely dominated by a more than 100% increase in paddy rice planting area in NE China. Long-term climate warming in the past, wide use of greenhouse nurseries, improved rice cultivars, agricultural subsidy policy, and a rising sale price of rice grain, taken together, boosted paddy rice expansion in NE China. Specifically, climatic warming and technological advances play a more important role in China, while social and economic factors, such as trade and agriculture policies, are critical in the two developed countries Japan and South Korea, shown in the decreased trend of paddy rice area. Our analysis linking climatic and socioeconomic factors to paddy rice expansion is to some degree constrained by the data limitation of driving factors (e.g., relatively short period and disparate data types) and other factors such as potential temporal autocorrelations; therefore, future studies are needed to conduct systematic and comprehensive investigations on the relative roles of climatic, socioeconomic, and cultural factors in the coupled human-natural paddy rice agriculture system. As air temperature, human population, and demand for rice continue to rise in the 21st century, NE China, and potentially the Russian Far East region, is likely to experience more northward expansion of paddy rice into potentially suitable cultivated lands. Therefore, it is imperative to monitor the spatial-temporal dynamics of paddy rice agriculture and assess its ecological and environmental consequences in NE Asia, a climate sensitive region affecting billions of people.

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