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Large increases of paddy rice area, gross primary production, and grain production in Northeast China during 2000–2017

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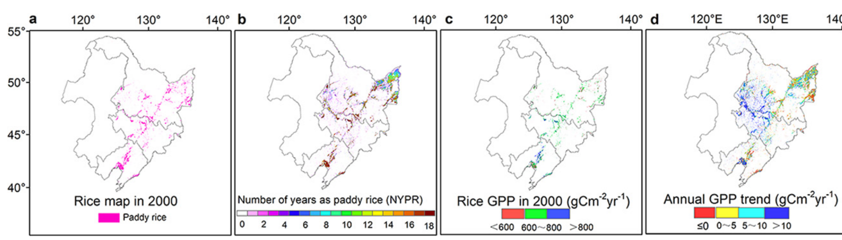
HIGHLIGHTS

- Paddy rice planting area increased substantially in Northeast China during 2000–2017.
- Paddy rice GPP and grain production rose by 157% and 118% during 2000–2017, respectively.
- New paddy rice fields could have moderate potential to increase annual GPP.

GRAPHICAL ABSTRACT



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ABSTRACT

China is the largest rice producer and consumer in the world. Accurate estimations of paddy rice planting area and rice grain production is important for feeding the increasing population in China. However, Southern China had substantial losses in paddy rice area over the last three decades in those regions where paddy rice has traditionally been produced. Several studies have shown increased paddy rice area in Northeast China. Here we document the annual dynamics of paddy rice area, gross primary production (GPP), and grain production in Northeast China (Heilongjiang, Jilin and Liaoning provinces) during 2000–2017 using agricultural statistical data, satellite images, and model simulations. Annual maps derived from satellite images show that paddy rice area in Northeast China has increased by 3.68 million ha from 2000 to 2017, which is more than the total combined paddy rice area of North Korea, South Korea, and Japan. Approximately 82% of paddy rice pixels had an increase in annual GPP during 2000–2017. The expansion of paddy rice area slowed down substantially since 2015. Annual GPP from those paddy rice fields cultivated continuously over the 18 years were moderately higher than that from other paddy rice fields, which suggested that improved management practices could increase grain production in the region. There was a strong linear relationship between annual GPP and annual rice grain production in Northeast China by province and year, which illustrates the potential of using satellite-based data-driven model to track and assess grain production of paddy rice in the region. Northeast China is clearly an emerging rice production base and plays an increasing role in crop production and food security in China. However, many challenges for the further expansion and sustainable cultivation of paddy rice in Northeast China remain.

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1. Introduction

The world's population is projected to increase to nine billion by 2050, and feeding nine billion people is a grand challenge for the global society (Godfray et al., 2010). As the most populous country in the world, crop production and food security in China has always been a major concern that has shaped national agricultural and economic policies and the world's food market. Since the publication of *Who Will Feed China?* (Brown, 1996), several studies have addressed food production and food security in China (Chen et al., 2014; Kang et al., 2009; Khan et al., 2009; Lu et al., 2015). China is the largest producer and consumer of rice grain in the world, accounting for 30% of global rice production and 28% of global rice consumption according to the FAOSTAT data in 2017. However, rapid development of its economy (industrialization, infrastructure, and urbanization) (Chen, 2007; Deng et al., 2006, 2008) since the early 1980 s has resulted in substantial losses of paddy rice area in Southern China where paddy rice has traditionally been grown. According to the National Bureau of Statistics of China, paddy rice area in southern China had already lost by approximately 12% from 1999 to 2017. Such losses of paddy rice area in Southern China has posed a major challenge for China's self-sufficiency in rice production and food security (Ghose, 2014; Liu et al., 2005, 2012, 2014, 2015).

In an effort to meet the need of rice production in China, paddy rice cultivation expanded in Northeast China, primarily in Heilongjiang, Jilin, and Liaoning provinces. A number of driving factors, including global warming, advancements in agricultural technology, market demand, and agricultural policies have led to the expansion of paddy rice in Northeast China over the most recent decades (Clauss et al., 2016; Deng et al., 2006, 2015, 2016a; Fan et al., 2016; Liu et al., 2013). In addition, many Chinese people believe that rice grains in Northeast China taste much better rice grains in Southern China and have less concern for soil and water pollution, which has also contributed to higher profits for rice farms and the expansion of paddy rice areas in Northeast China (Hansen et al., 2001). Thus, the rapid expansion of paddy rice area in Northeast China has made the region an emerging paddy rice production base (Fan et al., 2012). The agricultural statistical dataset reports that total paddy rice planting area in Northeast China increased from 2.68 $\times$ 10^6 ha in 2000 to 5.62 $\times$ 10^6 ha in 2017, with an increasing rate of 0.16 $\times$ 10^6 ha per year. Several studies have also used satellite remote sensing data, from the Moderate-Resolution Imaging Spectroradiometer (MODIS), to estimate rice paddy area in Northeast China (Clauss et al., 2016; Dong et al., 2016b; Zhang et al., 2015a, 2017a), which shows satellite remote sensing is an effective tool for quantifying paddy rice area at local and regional scales. Although there are discrepancies in the estimates of paddy rice area between the remote sensing approach and the agricultural statistical reports, all the previous studies agreed that paddy rice area has rapidly expanded in Northeast China.

In addition to paddy rice area dynamics, accurate information on gross primary production (GPP), grain production (GP), and paddy rice yield under climate change and agricultural management is also important for the study of crop production and food security at local and regional scales. Several satellite-based global GPP data products are available, such as the Terra/MODIS Gross and Net Primary Production (GPP/NPP) data product (MOD17A2) (Zhao et al., 2005) and the GPP dataset from the Vegetation Photosynthesis Model (VPM) (Zhang et al., 2017b). These two datasets were evaluated and applied to assess the spatial-temporal dynamic and trends of GPP across various biomes in China (Ma et al., 2019; Ping et al., 2019; Zhong et al., 2019). However, to date there are no systematic data syntheses and analyses of paddy rice planting area, gross primary production, grain production, and their driving factors in Northeast China during 2000–2017.

The objective of this study was to better quantify and understand the spatial-temporal dynamics, potential, and challenges of paddy rice agriculture in Northeast China. First, we used satellite remote sensing to generate annual maps of paddy rice during 2000–2017 and documented the spatial-temporal dynamics of paddy rice. Second, we used a satellite-based model to estimate annual GPP of paddy rice during 2000–2017, quantified the interannual dynamics of annual GPP of paddy rice, and determined the differences in annual GPP between those crop fields that have been continuously cultivated with paddy rice (18 year of rice cultivation) and those fields that were not cultivated continuously with paddy rice (varying between 1 and 17 years of rice cultivation). A majority of the paddy rice was non-continuously cultivated. Third, we investigated the relationship between annual GPP and annual grain production of paddy rice by province and year and assessed the potential of annual GPP derived from the satellite-based GPP model as a tool to estimate annual rice grain production in the region. Finally, we analyzed several driving factors and discussed the potential and challenges of paddy rice agriculture in Northeast China.

2. Materials and methods

2.1. Study area

Northeast China is composed of Heilongjiang, Jilin, and Liaoning Provinces, ranging between 121.146–123.620 °E and 38.713–53.546 °N. Its topography has a mixture of mountains and plains. The local climate is characterized as cold temperate and humid and sub-humid climate (Zhang et al., 2015a). One crop per year is cultivated under such thermal conditions in this region. Northeast China is one of the most important grain production regions in China, where maize (*Zea mays*), rice (*Oryza sativa*), soybean (*Glycine* max), and spring wheat (*Triticum aestivum*) are the four major crop types.

2.2. Geospatial datasets

2.2.1. Annual maps of paddy rice in Northeast China during 2000–2017

A phenology-based paddy rice mapping tool driven by MODIS data with a 500-m spatial resolution (RICE-MODIS) has been used to map paddy rice in Southern China in 2005 (Xiao et al., 2005), Southeast Asia in 2006 (Xiao et al., 2006), Northeast Asia during 2000–2014 (Dong et al., 2016b), and China and India during 2000–2015 (Zhang et al., 2017a). The Rice-MODIS mapping tool is based on a key feature of paddy rice fields during transplanting and early rice growing phases, which is a mixture of rice plants and water. These paddy rice maps were assessed by diverse data including filed photos (http://www.eomf.ou.edu/photos), very high spatial resolution (VHSR) images (e.g., IKONOS), and existing land use maps such as the China National Land Cover/Use Datasets (NLCD) (Liu et al., 2005, 2014). All of these validation (or accuracy assessment) activities showed that these paddy rice maps had reasonably high accuracy (Dong et al., 2016b; Zhang et al., 2015a, 2017a). In our study, we used the annual paddy rice maps during 2000–2014 (Dong et al., 2016b) and applied the same RICE-MODIS mapping tool to generate annual paddy rice maps for 2015–2017. Detailed information about the paddy rice mapping algorithms and the annual paddy rice maps during 2000–2017 (Fig. S1) were included in the supporting information.

2.2.2. Gross primary production of paddy rice in Northeast China during 2000–2017

We used the gross primary production (GPP) data from simulations of the satellite-based Vegetation Photosynthesis Model (VPM) (Zhang et al., 2017b). Detailed information about the model parameters and annual GPP data of paddy rice from 2000 to 2017 (Fig. S2) are documented in the Supporting Information. The GPP_{VPM} data have been evaluated using estimated GPP data (GPP_{EC}) from four paddy rice CO_2 flux tower sites, which showed the potential of the VPM model and MODIS images for estimating GPP of paddy rice (Xin et al., 2017). GPP_{VPM} data are used to estimate vegetation phenology from the perspective of plant physiology. The starting date of growing season (SOS) is the date when GPP_{VPM} rose to a threshold of >= 1 g C/m^2/day in spring and the ending date of growing season (EOS) is the date when GPP_{VPM} first dropped below >= 1 g C/m^2/day in fall (Chang et al., 2019; Nguy-Robertson et al., 2015; Xin et al., 2017; Zhang et al., 2018). For individual pixels, we calculated annual maximum GPP (GPP_{max}) and delineated the carbon uptake period (CUP) in a year by counting the number of days with daily GPP_{VPM} >= 1 g C/m^2/day.

2.2.3. Agricultural statistical data during 2000–2017

The datasets of population, gross domestic product (GDP), paddy rice planting area (ha), rice grain production (ton/yr), and fertilizer use amount in Northeast China by province and the entire country in 2000–2017 were obtained from the agricultural statistical reports (http://data.stats.gov.cn/). Producer price of rice and rice grain trade amount ($) in 2000–2016 for China were downloaded from FAOSTAT (http://www.fao.org/faostat/en/#data). The producer price of rice and rice grain trade amount ($) in 2017 were not yet available. Previous studies suggested that carbon constitutes about 45 percent of crop grain production (Lobell et al., 2003; West et al., 2011). Therefore, we calculated the carbon content of rice grain production (g C/yr) as 0.45 of rice grain production (ton/yr), which then allows us to investigate the relationship annual GPP and grain production of paddy rice in Northeast China.

2.3. Statistical analyses

2.3.1. Spatial-temporal expansion of paddy rice area during 2000–2017

We used annual paddy rice maps during 2000–2017 to quantify the spatial–temporal dynamics of paddy rice area in Northeast China. First, we counted the number of paddy rice pixels per year in the annual paddy rice maps with ArcGIS software to estimate the interannual changes in paddy rice area by province and for the entire Northeast China. Second, we overlaid annual paddy rice maps during 2000–2017 and generated a frequency (number of years as paddy rice, NYPR) map of paddy rice in Northeast China ($FREQ_{rice}$ or NYPR value range from 1 to 18). We designated those pixels with a $FREQ_{rice}$ or NYPR value of 18 as continuously cultivated paddy rice fields, and the remaining pixels ($FREQ_{rice}$ or NYPR value from 1 to 17) were designated as non-continuously cultivated paddy rice fields, which included newly converted, fallow, and abandoned paddy rice fields. Note that the paddy rice cultivation was likely to last many years once a field was converted to rice paddy.

2.3.2. Interannual variation and trends of annual GPP of rice paddies during 2000–2017

We aggregated the 8-day GPP data into annual GPP data for each pixel. The resultant annual GPP dataset during 2000–2017 were then summed up by provinces and for Northeast China as a whole. We applied the simple linear regression model (GPP = a + b * Year + error) to calculate the interannual trends of annual GPP during 2000–2017 for individual pixels. We calculated the mean and standard deviation of annual GPP for the continuously-cultivated paddy rice pixels (NYPR = 18 years) and the non-continuously cultivated paddy rice pixels (NYPR = 1 to 17 years), and then we calculated the differences in annual GPP between these two types of paddy rice pixels. We used the differences in annual GPP (or GPP gap) as an indicator of "yield gap" in those years between these two types of paddy rice pixels, as there are strong linear relationships between annual GPP and rice grain production.

2.3.3. Relationship between annual GPP and grain production of paddy rice during 2000–2017

We used a simple linear regression model to analyze provincial-level data of GPP (GPP) and grain production (GP) of paddy rice during 2000–2017 in Northeast China (3 provinces and 18 years). The model is expressed as a simple equation: GP = GPP * HI_{GPP} where HI_{GPP} is Harvest Index, defined as the ratio between grain production and GPP. Note that HI_{GPP} is different from the widely used Harvest Index (HI) that is defined as the ratio between grain production and aboveground biomass (AGB) (GP = AGB * HI_{AGB}) or as the ratio between grain production and net primary production (NPP) (GP = NPP * HI_{NPP}) (Guan et al., 2016; Lobell et al., 2002).

3. Results and discussion

3.1. Spatial-temporal dynamics of paddy rice planting area during 2000–2017

Fig. 1a shows the spatial distribution of paddy rice fields in 2000 in Northeast China and Fig. 1b illustrates the spatial-temporal changes of paddy rice fields over years during 2000–2017. Large increases in paddy rice area occurred in Sanjiang Plain, Heilongjiang Province. According to our MODIS-based annual paddy rice maps (Fig. 2a), total paddy rice planting area in Northeast China ranged from 2.56 $\times$ 10^6 ha in 2000 to 6.25 $\times$ 10^6 ha in 2017, an increase of 3.68 $\times$ 10^6 ha (144%) and an average annual increase of 0.20 $\times$ 10^6 ha per year. The simple linear regression model shows an increase rate of 0.24 $\times$ 10^6 ha/yr (Fig. 2a). Therefore, the large expansion of paddy rice area in Northeast China clearly compensates the loss of paddy rice areas in Southern China and plays a significant role in China achieving self-sufficiency in rice grain production and reducing the amount of rice imported from the international market. Also note that this observed increase of paddy rice area during 2000–2017 in Northeast China was larger than the combined paddy rice area of North Korea, South Korea, and Japan, where a total of 196 million people lived in 2000.

We also used the agricultural statistical data to investigate the relative role of paddy rice planting area in Northeast China and the whole country (Fig. 2d, Fig. S3). Northeast China has four major crops (maize, soybean, paddy rice, and wheat) and has played an important role in crop production and food security in China (Frolking et al., 2002; Liu et al., 2010, 2014). Paddy rice has the second largest annual growth rate among the four major crops in Northeast China during 2000–2017 ($slope_{rice}$ = 0.14, R^2 = 0.91, $p < 0.001$), accounting for 17% of total crop planting area in Northeast China by 2017 (Fig. 2d). The large expansion of paddy rice planting area and large losses in soybean area in Northeast China during 2008–2013 were driven mostly by the high market price for rice (perceived as high quality, organic, and low pollution) and a low market price for soybeans in the recent years (Dong et al., 2016b). Thus, farmers converted many soybean and maize fields into rice paddies over those years.

As the total paddy rice planting area in Southern China has declined in recent years and will likely continue to decline, mostly

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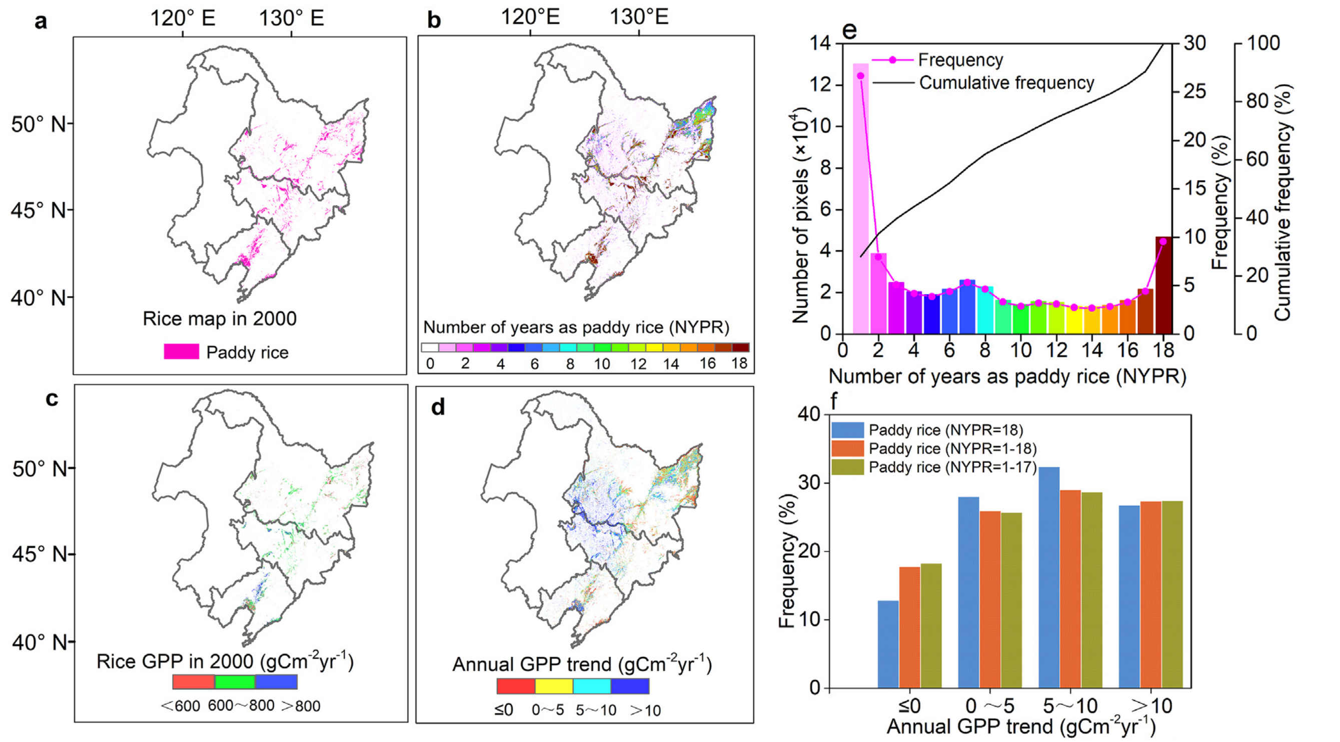

Fig. 1. Spatial distribution of rice paddies and annual gross primary production (GPP) in Northeast China during 2000–2017. (a) annual map of paddy rice in 2000; (b) the frequency map of paddy rice during 2000–2017; (c) annual GPP of paddy rice in 2000; (d) the trend of annual GPP of paddy rice during 2000–2017; (e) histogram of paddy rice during 2000–2017, based on (b); (f) histogram of the slope value of annual GPP trends during 2000–2017, based on (b) and (d); The blue column is for the continuously cultivated paddy rice pixels (NYPR = 18 years); the yellow column is for all the paddy rice pixels (NYPR = 1, 2., …, 18 years); the green column is for the non-continuously cultivated paddy rice pixels (NYPR = 1,2, …, 17 years). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

due to urbanization, infrastructure, and industrial development (Su et al., 2011; Zhang et al., 2009), the large expansion of paddy rice planting area in Northeast China has helped the country to avoid substantial declines in total paddy rice area, which can help ensure China's self-sufficiency in rice production and food security. It is projected that by 2030 China needs to produce about 20% more rice grain in order to meet its domestic demand for rice, assuming that rice consumption per capita is to be maintained at the current level (Peng et al., 2009). Therefore, the expansion of paddy rice area in Northeast China may continue into the foreseeable future.

There were large discrepancies in cropland area estimates from the remote sensing and agricultural statistics approaches, and under-reporting of cropland areas from the agricultural statistical data in China has been a common problem (Xiao et al., 2003). Paddy rice area in 2014 from our MODIS-based approach was 5.63×10^6 ha, which is ~ 25% larger than reported by the agricultural statistical data (~4.51×10^6 ha) (Fig. 2c). Another study analyzed 3200 Landsat 8 OLI images in 2014 and generated an annual map of paddy rice planting area in Northeastern Asia (Northeast China, North Korea, South Korea, and Japan) at 30-m spatial resolution, and it reported approximately 6.25×10^6 ha of paddy rice planting area in Northeast China in 2014 (Dong et al., 2016a), which is ~ 39% higher than the area estimate from the agricultural statistical data (~4.51×10^6 ha) and ~ 11% higher than the area estimate from this study (~5.63×10^6 ha). The comparison of paddy rice planting areas during 2000–2017 between our MODIS-based approach and the agricultural statistics approach (Fig. S4) show the strong linear relationship between these two datasets at the provincial scale (R^2>=0.98, P < 0.001). In comparison to the large increase of paddy rice area between 2000 and 2012 (Dong et al., 2016b), paddy rice area expansion in 2015–2017 was relatively small (Fig. 2), which may suggest that paddy rice area expansion is reaching its upper limit under current climate, technologies, and markets.

3.2. Spatial-temporal dynamics of gross primary production and grain production of paddy rice during 2000–2017

We calculated annual gross primary production (GPP) of rice paddies (Fig. 1c, Fig. S2, Fig. 3a) and estimated the trends of annual GPP of rice paddies in Northeast China (Fig. 1d, f, Fig. S5). Annual GPP of paddy rice area in Northeast China (Fig. 3a) has increased from 17.67×10^{12} g C/yr in 2000 to 45.38×10^{12} g C/yr in 2017, with an increase of 27.71×10^{12} g C/yr (157%) and an average annual increase rate of 1.54×10^{12} g C/yr over the 18-year period. The simple linear regression shows an increase rate of 1.88×10^{12} g C/yr (Fig. 3a). Heilongjiang Province had the largest annual paddy rice GPP among the three provinces in Northeast China (Fig. 3a). Annual paddy rice GPP decreased slightly in 2003, 2008, and 2015 (Fig. 3a), driven in part by a decrease in paddy rice planting area in those years (Fig. 2a). The drop in annual GPP in 2013 (Fig. 3a) was mostly driven by major floods in August, which were considered the largest floods of the last two decades (Zhang et al., 2015b, 2016a). Agricultural statistics during 2010–2017 showed that the percentage of crop area affected by floods and typhoons in Northeast China was the highest in 2013 (Table S1). Average annual precipitation in Northeast China from the NECP-DOE Reanalysis 2 dataset was the highest in 2013 (Fig. S6, S7, S8). The inter-annual trend of annual GPP ranged from − 10 to 20 g C/m^2/yr among 98.4% of the paddy rice fields, and the majority of the paddy rice fields (82.2%) experienced a positive trend in annual GPP during 2000–2017 (Fig. 1d, f).

The agricultural statistical dataset reported that annual grain production of paddy rice has increased from 17.94×10^{12} g/yr in

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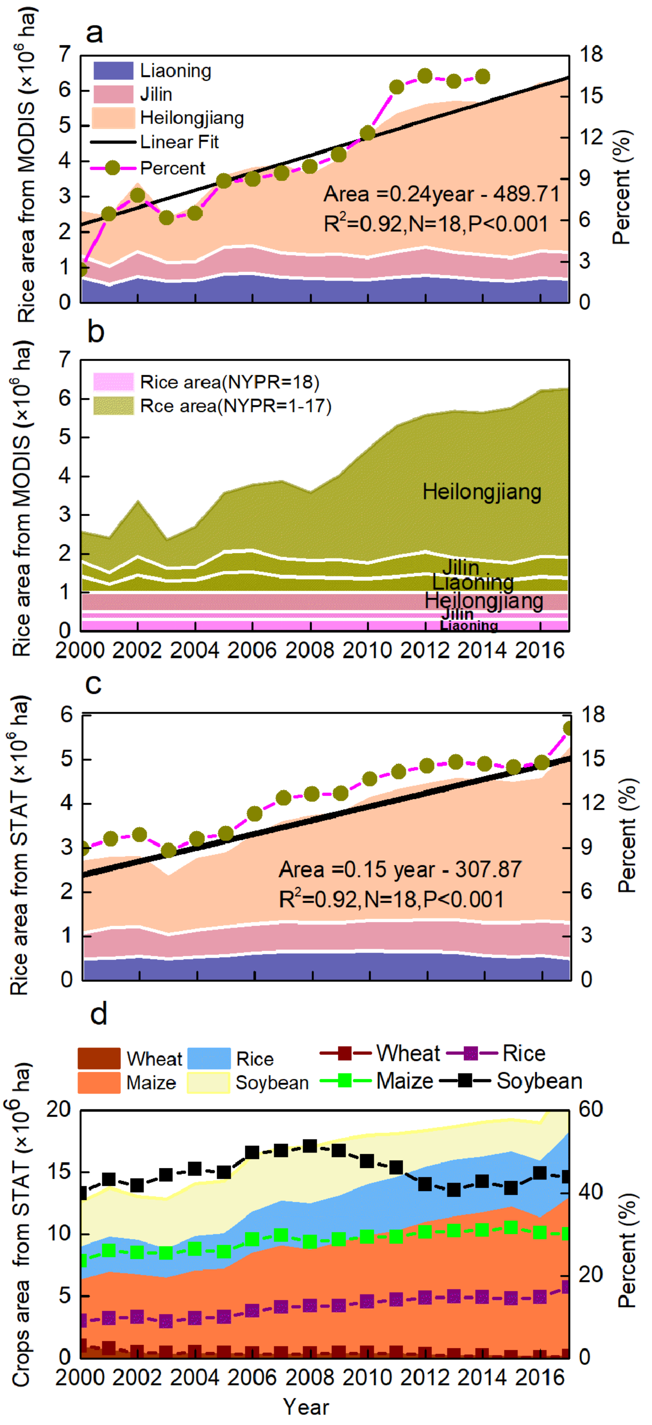

Fig. 2. Interannual variations of cropland area by province in Northeast China during 2000–2017. (a) paddy rice planting area by province from our MODIS-based paddy rice maps, the linear fit line is about total annual paddy rice area in Northeast China over years and the percent during 2000-2014 is the proportion of paddy rice area in Northeast China over the total paddy rice area in China; (b) paddy rice planting area by province and number of years as paddy rice (NYPR) from our MODIS-based paddy rice maps; (c) paddy rice planting area by province from the agricultural statistics, the linear fit line is about total annual paddy rice area in Northeast China over years and the percent is the proportion of paddy rice area in Northeast China over the total paddy rice area in China; and (d) planting areas of four major crops in Northeast China from the agricultural statistics during 2000–2017. We used the planting area of individual crops for all of Northeast China from the agricultural statistics as the denominator to calculate the percentage of individual crops in Northeast China.

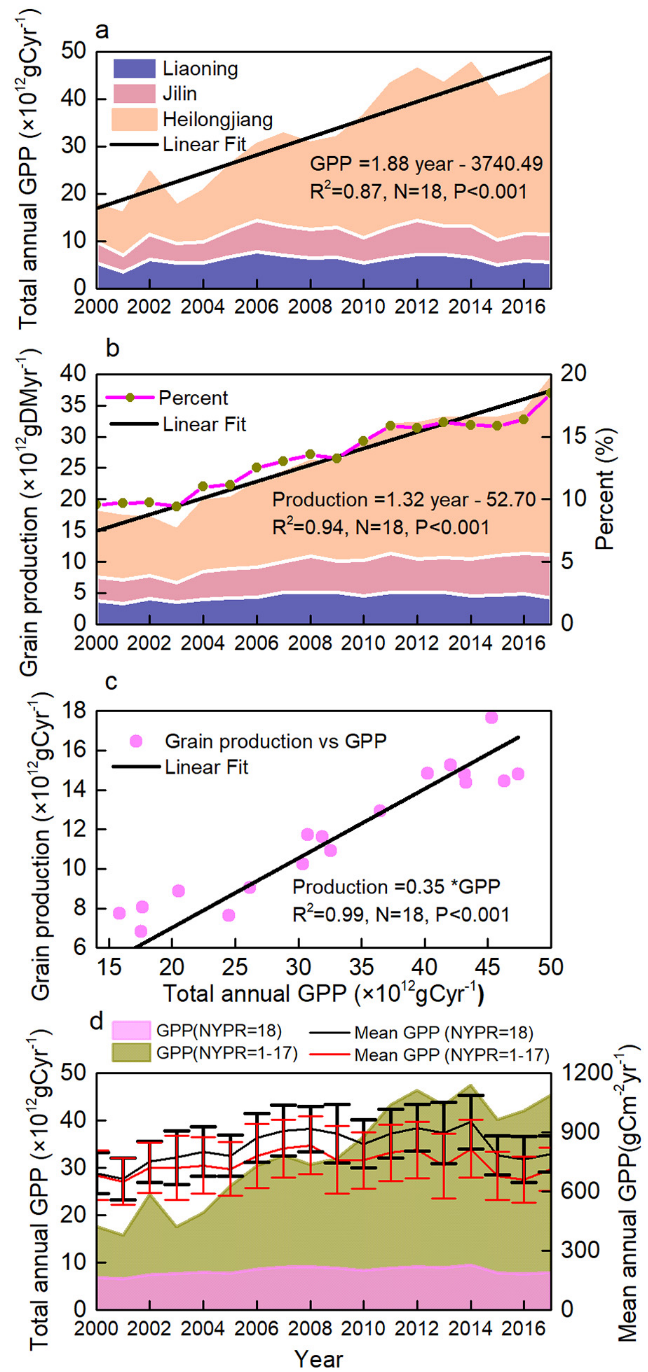

Fig. 3. Interannual variation of annual GPP and grain production of paddy rice by province in Northeast China during 2000–2017. (a) annual GPP by province from the VPM model and the linear fit line is about total annual GPP in Northeast China over years; (b) annual rice grain production by province from the agricultural statistics, the linear fit line is about total annual rice grain production in Northeast China over years and the percent is the proportion of rice grain production in Northeast China over the total rice grain production in China; (c) the relationship between annual GPP and annual grain production of paddy rice in Northeast China; (d) Total annual GPP and mean annual GPP with one standard deviation from the continuously cultivated rice paddies (NYPR = 18 years) and non-continuously cultivated rice paddies (NYPR = 1, 2, ..., 17 years).

2000 to 39.25 × 10^{12} g/yr in 2017 (dry matter weight), with an increase of 21.31 × 10^{12}g/yr (119%) and an average annual increase of 1.18 × 10^{12} g/yr over the 18-year period (Fig. 3b). Simple linear regression showed an increase of 1.32 × 10^{12} g/yr for rice grain production (Fig. 3b). Heilongjiang Province had the largest rice grain production in Northeast China (Fig. 3b). Note that the agricultural statistics data report that annual grain production of paddy rice had a slight decrease in 2003 and 2009, but no drop in 2013 in Northeast China (Fig. 3b), which was not consistent with the large flood event and the drop of annual GPP in 2013 (Fig. 3a). This discrepancy highlights the need and value of using satellite-based GPP data to track and assess the impacts of extreme climate events (e.g., flood or drought) on crop grain production and yield.

We examined the relationships between annual GPP and annual grain production of paddy rice by province and for Northeast China during 2000–2017 (Fig. 3c, Fig. S9). The Harvest Index (HI_{GPP}) is defined as the ratio between annual grain production (GP) and annual GPP (GPP) of paddy rice ($GP = GPP * HI_{GPP}$). The slope values (or HI_{GPP}) from simple linear regression models between annual grain production and annual GPP of paddy rice are 0.35 for Northeast China (Fig. 3c), 0.34 for Heilongjiang province, 0.33 for Liaoning province, and 0.41 for Jilin province (Fig. 3c, Fig. S9b). The HI_{AGB} or HI_{NPP} and grain production of various crops were often used to estimate above ground biomass (AGB) and net primary production (NPP) of crops in the United States (Lobell et al., 2002). The empirical HI_{AGB} values vary among the crop types. For example, 0.40 for rice and wheat, and 0.50 for corn (Kroodsma and Field, 2006). The statistically significant relationship between annual GPP and annual grain production of paddy rice in this study clearly shows that VPM-based GPP is a viable data source for estimating annual grain production of paddy rice in Northeast China.

3.3. The differences (or gaps) in annual GPP between continuously-cultivated and the non-continuously cultivated paddy rice fields

Many studies have investigated the crop yield gap, which is defined as the difference between yield potential (Yp) and average yield over years and/or space (Lobell, 2013; Lobell et al., 2009). We used annual GPP as a proxy for assessing rice yield gap as annual GPP is strongly correlated to annual grain production of paddy rice and the VPM-based GPP data agree reasonably well with GPP data from paddy rice CO_2 eddy flux tower sites (Xin et al., 2017). We calculated total annual GPP, mean annual GPP, and standard error between these two types of paddy rice pixels (Fig. 3d). The total annual GPP from those fields that were not continuously cultivated with paddy rice ranged from 10.73×10^{12} g C/yr in 2000 to 37.47×10^{12}g C/yr in 2017, much larger than the total annual GPP from those fields that were continuously cultivated with paddy rice, ranging from 6.94×10^{12} g C/yr in 2000 to 7.91×10^{12}g C/yr in 2017. However, the mean annual GPP for continuously-cultivated paddy rice ranged from 694 ± 103 g C/m^2/yr in 2000 to 952 ± 136 g C/m^2/yr in 2014, but dropped to 791 ± 93 g C/m^2/yr in 2017. These values are moderately higher than the mean annual GPP from non-continuously cultivated paddy rice, which ranged from 683 ± 126 g C /m^2/yr in 2000 to 817 ± 146 g C/m^2/yr in 2014 , and was 712 ± 109 g C /m^2/yr in 2017 (Fig. 3d). Mean annual GPP for all paddy rice decreased slightly in 2010, likely due to low growing season temperatures and precipitation (Fig. S8). The heatmap of the mean annual GPP (Fig. 4) shows that the mean annual GPP of the continuously-cultivated paddy rice was greater than non-continuously cultivated paddy rice. We combined all the pixels that were cultivated from one year to 17 years as the non-continuously cultivated paddy rice and calculated the mean annual GPP for all the pixels. Mean annual GPP for the continuously-cultivated paddy rice was greater than non-continuously cultivated paddy rice, and the difference (gap) in mean annual GPP (g C/m^2/yr) increased over time (Fig. 3d, Fig. 4). Continuously cultivated rice paddies are more likely to have good water and fertilizer management, which can mitigate the impacts of drought and/or flood compared to non-continuously cultivated paddy rice fields located in the northeastern Sanjiang Plain, the northern and western Songnen Plain, and the northwestern Liaohe Plain (Mueller et al., 2012). The moderate gaps in mean annual GPP between these two types of paddy rice in 2017 (79 g C/m^2/yr, ~10%) clearly suggested that there is a moderate potential for raising annual GPP in non-continuously cultivated paddy rice, maybe by various approaches, including water and nutrient management and advanced agricultural and biological technologies.

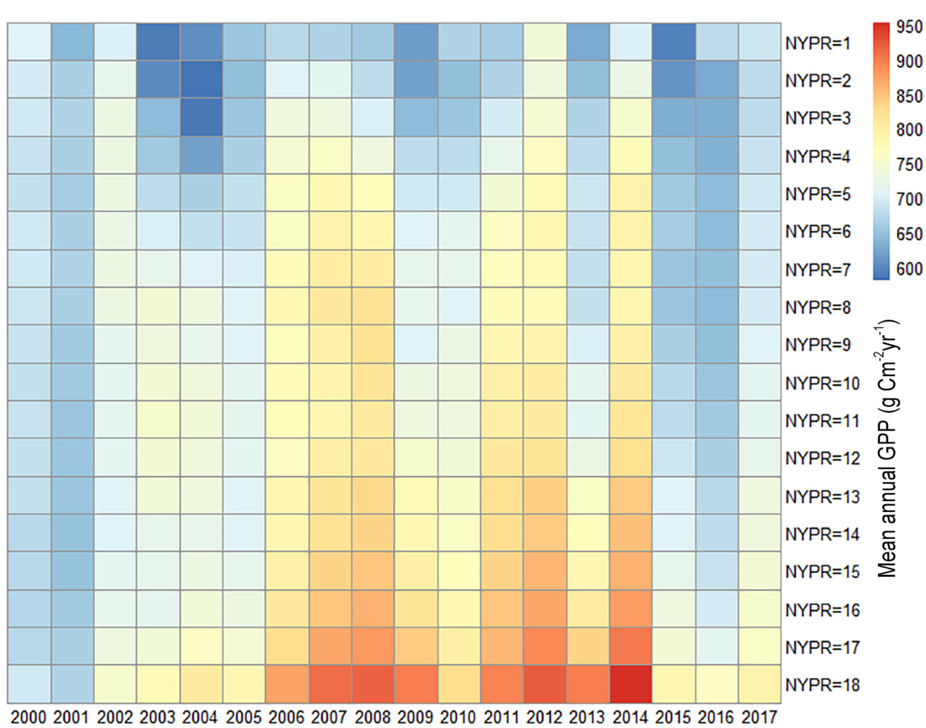

Fig. 4. Heatmap of mean annual GPP in those pixels with different number years of paddy rice (NYPR) during 2000–2017.

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3.4. Factors contributing to the increases of annual GPP of paddy rice during 2000–2017

Climate change, specifically global warming, can prolong the growing season and carbon uptake period (CUP) by plants. A number of studies have reported that annual GPP of vegetation is jointly controlled by physiology (using maximum daily GPP in a year as an indicator, GPP_{max}) and phenology (using CUP in a year as an indicator) (Xia et al., 2015, 2017; Zhang et al., 2016b). Our results also show that annual GPP of paddy rice in Northeast China is jointly controlled by physiology and phenology (Fig. 5a, b, c) for all rice pixels. Annual GPP increased as the carbon uptake period became longer, which could be due to shifts in the cultivars used in the region over the past decades (Tao et al., 2013). Annual GPP also increased as the daily maximum GPP in a year rose, which is affected by crop variety, temperature, solar radiation, water, nutrients, and fertilizers. GPP_{max} varied substantially, ranging from 10 g C/m^2/day to 15 g C/m^2/day (Fig. 5d, e, f). The CUP was in the range from 110 days to 124 days during 2000–2017 (Fig. 5g, h, i). These results show that GPP_{max} had relatively stronger contribution to annual GPP than did CUP (Fig. 5), which is consistent with the results reported in a study of various terrestrial ecosystems in North America (Zhou et al., 2017). These results also suggest that water and nutrient use and management are essential for continued increases of annual GPP and grain production of paddy rice in Northeast China during 2000–2017.

3.5. Challenging issues for expansion, intensification, and sustainability of paddy rice

Substantial increases in the annual GPP and grain production of croplands have been achieved using high-yield cultivars, chemical fertilizers, irrigation, and weed and pest control that has been a part of a so-called "green revolution" that has occurred over the last 50 years (Fan et al., 2012). The use of chemical fertilizers in China has increased linearly since 1961 and China is currently the world's largest consumer of fertilizers (Peng et al., 2009). In Northeast China, the total amount of N/P/K and compound fertilizers used for all crops increased from 3.43×10^6 ton/yr in 2000 to 6.28×10^6 ton/yr in 2017, with an increase of 2.85×10^6 ton/yr (~83%) (Fig. 6a). Annual paddy rice grain production in Northeast China has a strong linear relationship with annual total amount of N/P/K and compound fertilizers ($R^2 = 0.94$, $p < 0.001$) (Fig. 6a). It is well known that the over-use of chemical fertilizers can have many negative environmental impacts, including degradation of water quality (Du et al., 2015; Wu et al., 2016; Xue et al., 2014). However, a comprehensive assessment and monitoring of agricultural intensification and its environmental impacts in Northeast

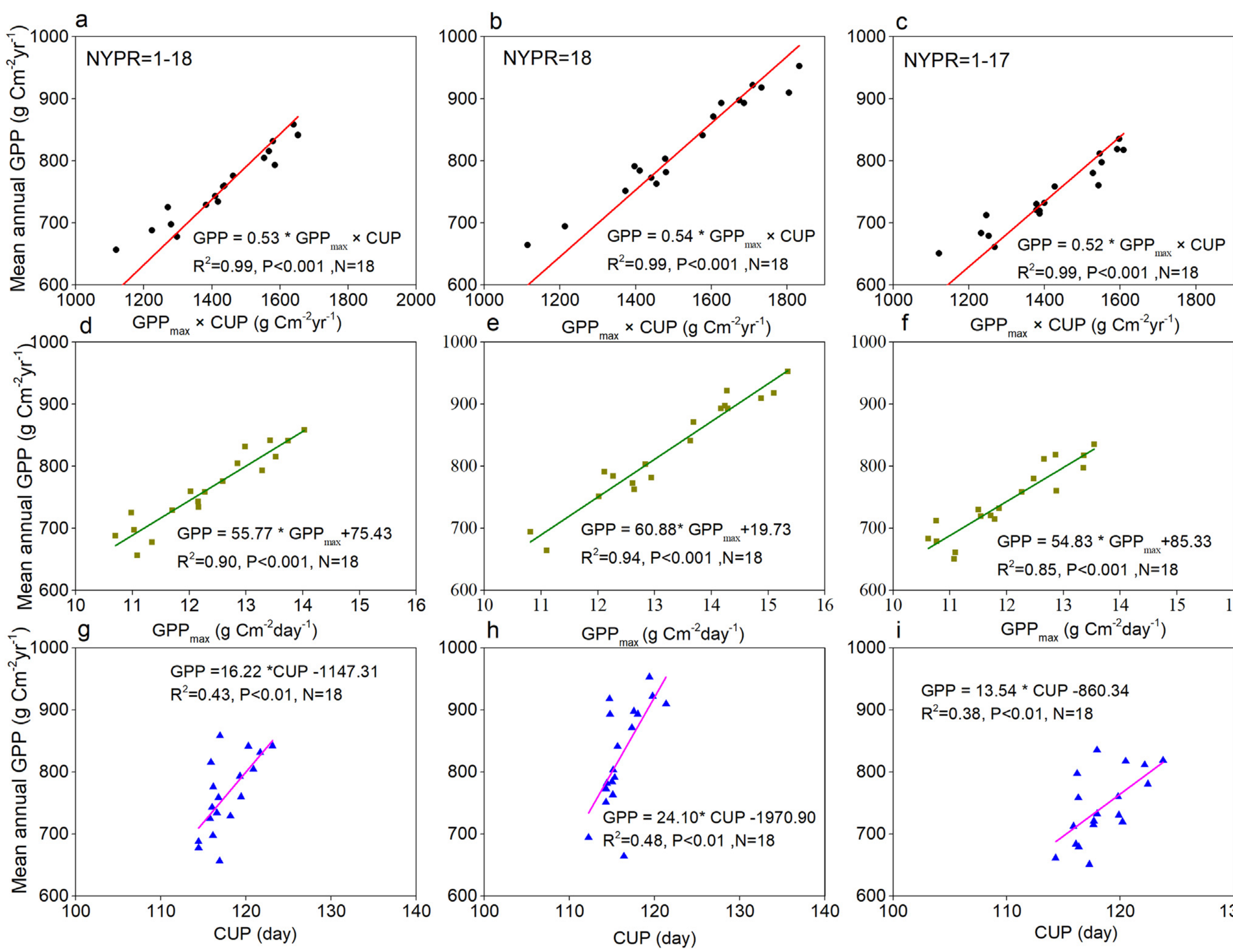

Fig. 5. Joint control of phenology and physiology on mean annual GPP (g C/m^2/yr) of paddy rice fields in Northeast China during 2000–2017. Phenology is represented by carbon uptake period (CUP; days) and physiology is represented by maximum daily GPP (GPP_{max}) in the growing season. The left column is for all paddy rice pixels (NYPR = 1–18 years), the middle column is for the continuously cultivated paddy rice pixels (NYPR = 18 years), and the right column is for the non-continuously cultivated paddy rice pixels (NYPR = 1, 2, …, 17 years).

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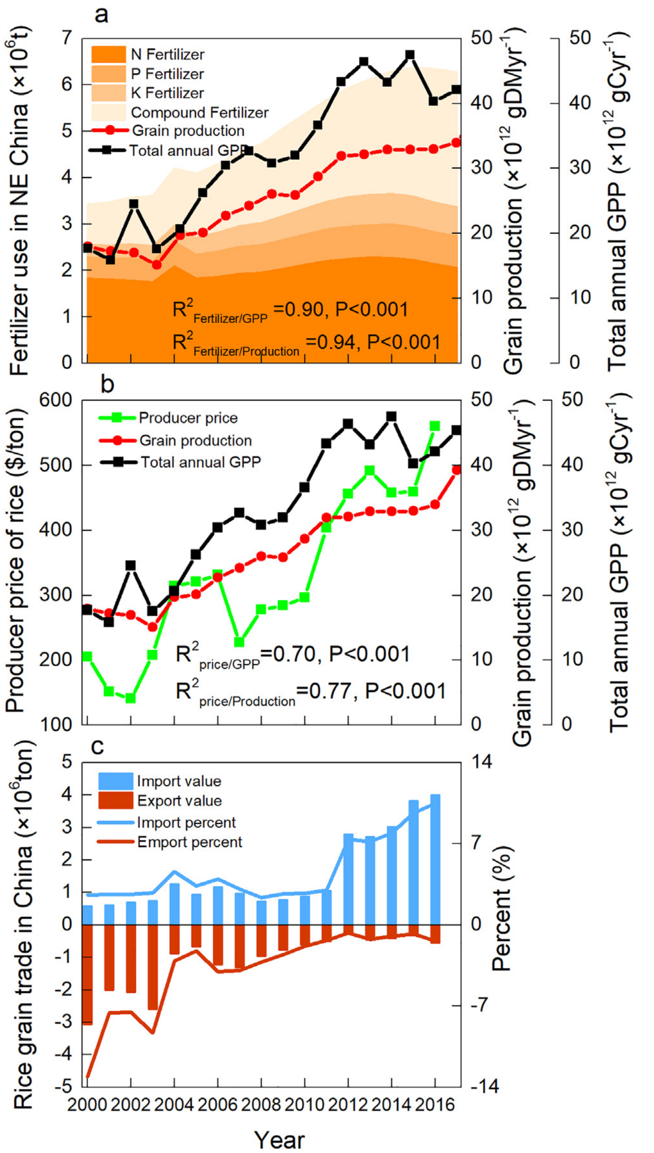

Fig. 6. Interannual variations of (a) fertilizer use, grain production and total annual GPP during 2000–2017 in Northeast China, (b) producer price of paddy rice during 2000–2016 in China, (c) import and export amounts of rice grain during 2000–2016 in China and the percent is the proportion of paddy rice trade amount in China over the total paddy rice trade in the globe.

China has not yet been done. Adverse impacts from intensification of paddy rice production could threaten the emergence of Northeast China as a paddy rice production base, which is essential for China to achieve self-sufficiency in rice grain production (Mueller et al., 2012).

Cultivation of paddy rice requires a large amount of water, and thus water availability, accessibility, and reliability are important for paddy rice production in Northeast China (Du et al., 2015; Lu et al., 2016). The observed large expansion of paddy rice in Northeast China in the past 18 years has resulted in substantial changes in water use and management in the region, including the pumping of groundwater for irrigation and flooding, inter-basin water transfers from major rivers to rice paddies through a network of irrigation channels, and construction of reservoirs. The use of groundwater for irrigation may result in a loss of groundwater if precipitation does not sufficiently recharge aquifers. The long-distance transfer of water from major rivers may increase land water storage in the regions where paddy rice field are abundant. To date, there is no comprehensive quantification of the spatial-temporal changes in surface water body and ground water in Northeast China nor an assessment of their consequences on the water cycle and climate.

Rice paddies are often used by domestic and wild waterfowl. At present, paddy rice and domestic duck systems are not popular in the region, but rice grains from these fields are often considered to be high quality grain with a high market price. Northeast China is an important stopover area during spring and fall bird migration. Thus, newly expanded rice paddies and surface water bodies (reservoirs, irrigation channels, ponds) in the Northeast China could serve as new habitat for birds, which could have positive benefit for bird conservation but potentially negative consequences because the congregation of wild and domestic birds can increase the occurrence of avian influenza viruses (Gilbert et al., 2017).

The large expansion of rice paddies in Northeast China since 2000 was driven by national agricultural policy and high market prices for rice relative to other crops, and the expansion was enabled by global warming and agricultural technology (Dong et al., 2016b). Annual GPP, grain production, and producer price in Northeast China have similar trends over years (Fig. 6b). The producer price of paddy rice commodities rose from ~ US$205 per metric ton in 2000 to US$559 per metric ton in 2016. The producer price has a stronger linear correlation with annual grain yield ($R^2 = 0.77$) and annual GPP ($R^2 = 0.70$). According to the rice grain import and export data from the FAOSTAT dataset, annual rice grain export in China was more than rice grain import during 2000–2008, but in 2009 rice grain import started to exceed rice grain export (Fig. 6c). This reversed import-export situation is likely to be driven by many factors, including large losses in rice paddy area in Southern China due to urbanization, industrialization, infrastructure, and water and soil pollution. According to FAOSTAT, global rice trade value reached 40 million metric tons in 2016 and China rice trade accounted for 10.4% of global rice trade in 2016 (Fig. 6c). If China continues to increase its rice grain import, it could have substantial impacts on rice production and international trade in Asia and the world, as evidenced by its increasing import of corn and soybean grains over the past two decades.

4. Conclusions and perspectives

In this study we documented and analyzed the interannual variations and trends of paddy rice planting area, GPP, and grain production in Northeast China during 2000–2017. Our results highlighted the role of expansion and intensification of paddy rice in Northeast China for rice crop production and food security in China. The strong linear relationship between annual GPP from our data-driven VPM model and annual grain production from the agricultural statistical data illustrated the potential of using the VPM model to estimate annual GPP and then estimate annual grain production of paddy rice. The moderate gaps in annual GPP between continuously cultivated (18 years) and non-continuously cultivated rice paddies (1 to 17 years) highlighted the potential to increase total rice grain production in Northeast China by improving management of those non-continuously cultivated rice paddies, which, together with additional expansion of paddy rice planting areas, could help ensure rice production and food security in China. In addition, there is also an urgent need to gather more data, information, and knowledge on fertilizer use, irrigation water use and its sources, and climate change in Northeast China, which will improve our understanding and modeling of the complexity and nexus of food-water-energy systems

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and help our society to achieve sustainable expansion and intensification of paddy rice in Northeast China.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.135183.

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