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Effects of climate change on paddy expansion and potential adaption strategies for sustainable agriculture development across Northeast China

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ABSTRACT

Sustainably feeding an increasing population is a grand challenge in the context of climate change and rapid urbanization. Over the past decades, there has been a remarkable trend in paddy expansion into the mid-high latitude regions of Northeast Asia, especially in China. Yet, knowledge on paddy expansion patterns and corresponding responses to climate change and socioeconomic factors are limited. To bridge this gap, satellite-based land use data for 1990, 2000, 2010 and 2018 at 30-m resolution, as well as historical and projected climatic data (including ERA5 data for 1982–2019 and GCMs data of CMIP5 for 2006–2050) and diverse socioeconomic data, were utilized to investigate patterns and quality changes of paddy fields across Northeast China. Results showed that the 0 °C isotherm moved northward by 270 km during 1961–2000 and 190.5 km during 2000–2019. Net paddy area expanded by 2.6×10^4 km^2 in Northeast China during 1990–2018; in Heilongjiang Province, paddy area dramatically expanded by about 4.0×10^4 km^2 during 1958–2018, of which 1.8×10^4 km^2 and 2.2×10^4 km^2 increment in 1958–2000 and 2000–2018, respectively. Even though climate hiatus occurred around 2010, the expansion rate of paddy area in Northeast China was up to 1.76×10^3 km^2/a during 2010–2018. In addition to warming climate, improved agricultural technologies and physical inputs, increasing market demands, and agricultural policy implement were largely responsible for the paddy expansion in Northeast China. However, continuously cultivated paddy fields had generally more suitable natural conditions and better infrastructure than newly cultivated paddy fields. This study provides some potential suggestions for the sustainable development of modern agriculture in Northeast China.

1. Introduction

Rice production is indispensable for ensuring food security, as rice is the staple food for more than half of the world's population (Hu et al., 2019; Tilman et al., 2011; Zhang et al., 2019). Global demand for rice is expected to increase by nearly 30% until 2050 in view of steadily growing population, high and stable rice production is crucial for global sustainable development (Alexandratos & Bruinsma, 2012; Chen et al., 2020; Godfray et al., 2010). As a major producer and consumer of rice, China contributes approximately 30% to global rice production (FAOSTAT, 2020; Liu et al., 2020). Additionally, rice is the staple food for more than 80% of the population of China, and rice production with high-yielding and stable growth is of great importance to national food self-sufficiency (Zhang et al., 2019; Zhang et al., 2020).

However, sustainably feeding an increasing population is a grand challenge in the context of climate change and rapid urbanization (Chen et al., 2020; Cui et al., 2018; Godfray et al., 2010; Li et al., 2018a; Liu et al., 2021; Liu & Li, 2017). The significant urbanization and industrialization process was spatiotemporally coupled with a substantial loss of high-quality paddy areas in urban surroundings regions, especially in southeastern China; the loss rate has accelerated since 2005 (Bren D Amour et al., 2017; Li et al., 2018 a; Qiu et al., 2020). Meanwhile, rural-to-urban population migration also resulted in a decreased multiple cropping index of paddy rice and even paddy field abandonment in southern China, particularly the paddy fields in hilly rural regions with relatively unfavorable cultivation sites (Cocca et al., 2012; Li & Li, 2017; Yan et al., 2016). Considering the growing population and warming climate, over the past decades there has been a remarkable trend in paddy field expansion into the mid-high latitude regions of China to compensate for the paddy loss in southern China and achieve

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self-sufficiency (Dong et al., 2015; ; Dong et al., 2016; Liu et al., 2015; Xin et al., 2020).

Northeast China is regarded as the breadbasket of China, but has been disturbed by significant climate warming and intensive human activities during the past decades (Chen et al., 2020; Xia et al., 2014; Zhang & Song, 2019). Rice growth and productivity are highly sensitive to temperature fluctuations; lower temperature suppresses rice growth and grain filling, whereas higher temperature reduces rice yields in the southeastern China (Chen et al., 2020; Hu et al., 2019; Ling et al., 2019; Tao et al., 2013). Various researchers explored the response of rice yield to climate warming in terms of historical climate data and simulated future climate data, indicated that increased rice yield benefited from rising temperature in Northeast China during the past decades (Dong et al., 2015; Liu et al., 2020; Tao et al., 2013). However, continuous climate warming in the future might shorten rice growth duration, increase climate disaster frequency, and adversely impact rice yields (Hu et al., 2019; Zhang et al., 2019). Cultivated area change is a vital indicator reflecting the impact of climate warming on rice production (Gao & Liu, 2011; Godfray et al., 2010; Li et al., 2015; Liu et al., 2015; Xin et al., 2020). Gao and Liu (2011) indicated that the rice-growing area expanded nearly six times in Heilongjiang Province from the 1960s to the 2000s, which was largely due to the climate warming over 2 °C in most regions. Xin et al. (2020) utilized MODIS data at 500-m resolution to extract paddy fields and analyzed annual paddy area change in Northeast China for the period 2000–2017. However, spatially detailed knowledge on long-term paddy expansion patterns and the major contributors to new paddy fields in Northeast China are still limited. Most studies explored the relationship between continuously rising temperature and paddy yield change, while impacts of climate warming and climate hiatus on paddy area change still needed to be future explored. In addition, studies rarely compared the quality changes between new paddy fields and continuous paddy fields.

Therefore, the objectives of this study were (1) to investigate the spatial-temporal patterns of paddy fields in Northeast China during 1990–2018 at 30-m spatial resolution and link them with the research of Liu et al. (2005) and Gao and Liu (2011); (2) to clarify the response of paddy field expansion to climate change and other driving factors; (3) to compare quality differences between newly cultivated and continuously cultivated paddy fields, and attempt to provide some potential suggestions for sustainable agriculture development in Northeast China.

2. Data and methods

2.1. Study area

The Northeast China Plain, covering Heilongjiang, Jilin and Liaoning Provinces (121.1–123.6°E and 38.7–53.5°N), is the largest plain in China. The plain is made up of mostly black soil, one of the most fertile soils in China (Xu et al., 2010). The winter is frigid and the summer is cool; the annual temperature of ranges between -5 and 11 °C. Annual rainfall ranges from 400 mm to 1100 mm and is mostly concentrated in the summer. As one of the important grain-producing regions of China, with its mixture of mountains and plains coupled with a continental monsoonal climate and fertile soils, Northeast China is quite suitable for the growth of single-cropped rice.

2.2. Data and preprocessing

The meteorological data consisted of daily air temperature and daily precipitation on a 0.1° × 0.1° geographic grid for the period 1982–2019 and were obtained from the latest state-of-the-art ERA5 analysis datasets, which are reanalysis products based on the Integrated Forecast System of European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020; Muñoz-Sabater et al., 2021). A Python program was utilized to downscale the ERA5 analysis datasets from 0.1° × 0.1° to 1 km × 1 km to track in detail the isotherm movement in Northeast China.

Global climate models (GCMs) from the Coupled Model Intercomparison Project Phase Five (CMIP5) are widely used to project future climate change (Taylor et al., 2012; Wang et al., 2019; You et al., 2016; Zhang et al., 2019). The MRI-CGCM3, MIROC5 and CanESM2 perform better than the other GCMs for simulating the spatial-temporal evolution of hydrothermal conditions in China (Lv et al., 2019; Watanabe et al., 2010; Yukimoto et al., 2012; Zhang et al., 2019). The MRI-CGCM3, MIROC5 and CanESM2 datasets of the RCP4.5 scenario during 2006–2050 were collected. Considering model performance evaluation and data comparison, the outputs of the three GCMs were uniformly downscaled to 0.1° × 0.1° by using Python programs.

The 30-m spatial resolution land use data for 1990, 2000, 2010 and 2018 were collected from the Center for Resource and Environmental Science Data, Chinese Academy of Sciences (http://www.resdc.cn/) (Liu et al., 2014). The land use types include croplands (paddy fields and dry fields), woodlands, grasslands, water, construction land and unused land. The datasets have been widely used in previous studies of land use change and management in China (Liu et al., 2014; Li et al., 2018 b).

Various variables, including normalized difference vegetation index (NDVI), soil organic matter, digital elevation model (DEM), distance to river and distance to roads were obtained for quantitatively evaluating the quality of cultivated land (Wang et al., 2019). NDVI data was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD13A1 at 500-m resolution for the period of 2000–2018. Soil organic matter data were derived from the Harmonized World Soil Database (version 1.1) at 2009 with 1-km spatial resolution (http://geodata.pku.eud.cn). The 1-km DEM was collected from the NASA Shuttle Radar Topographic Mission (SRTM) (Fig. 1). The main river data were generated from the Centre for Resource and Environmental Science Data, Chinese Academy of Sciences (http://www.resdc.cn/), and the road network data were downloaded from the Open Street Map dataset (https://download.geofabrik.de). Other auxiliary data included paddy rice planting area (in ha) in Northeast China by province during 1990–2019, which were derived from the China Rural Statistical Yearbook, and producer rice prices (in $) during 1991–2019 were downloaded from FAOSTAT (http://www.fao.org/faostat/en/#data).

2.3. Statistics and analyses

2.3.1. Land use change

The spatial-temporal evolution of land use is generally measured by land use transfer matrix (Pontius et al., 2004; Zhou et al., 2020), which is calculated as:

$$K_{mn} = \begin{vmatrix} K_{11} & K_{12}\ldots & K_{1s} \\ K_{21} & K_{22}\cdots & K_{2n} \\ \vdots & \vdots & \vdots \\ K_{s1} & K_{s2}\ldots & K_{ss} \end{vmatrix} \tag{1}$$

where K_{mn} refers to the conversion area from land use m in the beginning period to land use n in the ending period, and s is the number of land use types. During the period 1990–2018, a transfer matrix was constructed among seven land use types (i.e., paddy fields, dry fields, woodland, grassland, water, construction land and unused land) for each decade by utilizing Python programing.

2.3.2. Trend analyses of the thermal condition distribution

Trend analyses is available for quantitatively exploring the thermal condition change in different regions of Northeast China during 1982–2019 to evaluate the land use change response to climate change (Piao et al., 2010; Wang et al., 2017). The regression coefficient (Slope) is computed by the following formula (Liu et al., 2019):

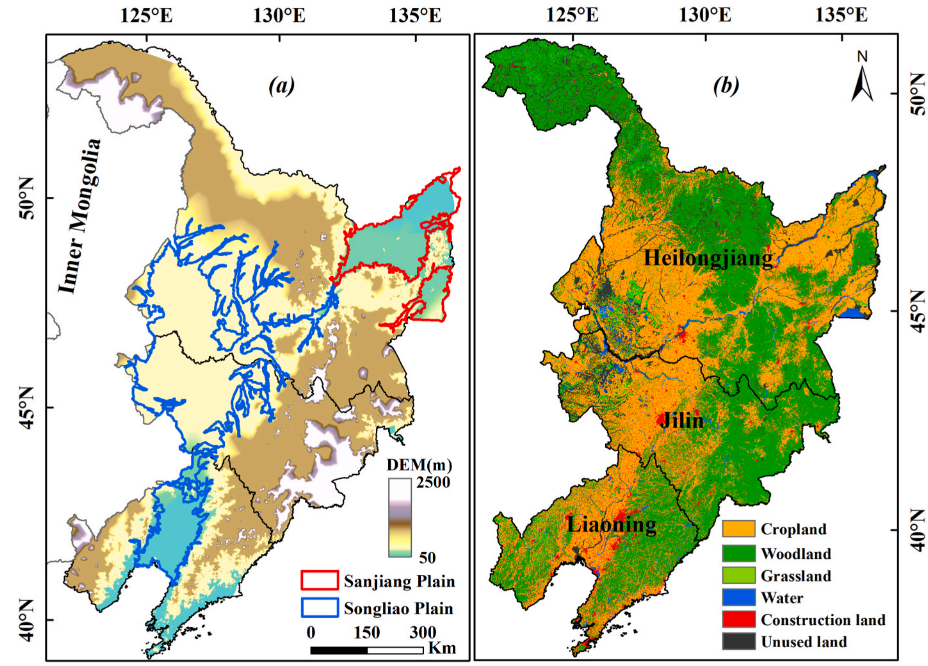

Fig. 1. Digital elevation model (DEM, a) and land use types of Northeast China in 2018 (b).

$$\text{Slope} = \frac{n\sum X_iT_i - \sum X_i \sum T_i}{n\sum X_i^2 - (\sum X_i)^2} \tag{2}$$

where X_i is the i th year, T_i is the annual temperature in the i th year and n is the number of years. The trend calculation was performed with Python 3.7, and the student's t-test was calculated to examine the statistical significance of the trend at 0.05 level or 0.01 level.

2.3.3. Barycenter relocation of cultivated land

Barycenter is the spatial point at which the powers reach a relative equilibrium in all directions. Various barycenter models have been frequently used to reflect spatial pattern changes of different objects (Meng et al., 2021; Wang et al., 2018; Zhang et al., 2012). In this study, a barycenter model is used to evaluate the transfer trajectory of cultivated land in Northeast China and is calculated as followed:

$$X_t = \sum_{i=1}^{n}(C_{ti} \times X_i) \Big/ \sum_{i=1}^{n} C_{ti} \tag{3}$$

$$Y_t = \sum_{i=1}^{n}(C_{ti} \times Y_i) \Big/ \sum_{i=1}^{n} C_{ti} \tag{4}$$

where X_t and Y_t are the longitude and latitude coordinates of the cultivated land barycenter in the tth year; C_{ti} refers to the area of cultivated land in unit i. The barycenter model of cultivated land is carried out with ArcGIS 10.2 software, and the barycenter displacement is calculated by the following formula:

$$Dis. = \sqrt{(X_{t1} - X_{t2})^2 + (Y_{t1} - Y_{t2})^2} \tag{5}$$

where $Dis.$ is the barycenter displacement of cultivated land; (X_{t1}, Y_{t1}) and (X_{t2}, Y_{t2}) are the barycentric coordinates for years t_1 and t_2, respectively.

2.3.4. Evaluating GCMs performance from CMIP5

Spatial correlation (SC) and relative root-mean-square error (RRMSE) are widely used to quantitatively evaluate the GCMs performance from CMIP5, and further illustrate the explanatory power of simulated climate data derived from different GCMs (Wu et al., 2013; Lv et al., 2019). SC reflects the spatial distribution similarity between simulated and observed data and is calculated as followed:

$$SC = \frac{\sum_{I=1}^{N}(R_{FI} - \overline{R_F})(R_{OI} - \overline{R_o})}{\sqrt{\sum_{I=1}^{N}(R_{FI} - \overline{R_F})^2 \sum_{I=1}^{N}(R_{OI} - \overline{R_O})^2}} \tag{6}$$

where N is the pixel number in Northeast China; R_{FI} and R_{OI} are the simulated value and observed values at pixel I, respectively; $\overline{R_F}$ and $\overline{R_o}$ represent the average simulated value and average observed value in the study area. A greater SC represents higher similarity in the spatial distribution and vice versa. In this study, the SC values of three GCMs from CMIP5, i.e. MRI-CGCM3, MRIOC5, CanESM2, were generated separately by using air temperature data of each GCM and of ERA5 for the period 2006–2019. Moreover, the air temperature data of each GCM were uniformly downscaled to $0.1^\circ \times 0.1^\circ$ by utilizing a Python program in order to match the ERA5 dataset.

In addition, the intensity difference between simulated and observed data is illustrated by RRMSE, which is computed by the following formula:

$$RRMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i - \overline{E})^2} \tag{7}$$

$$E_i = \frac{R_{FI} - R_{OI}}{R_{oi}} \tag{8}$$

$$\overline{E} = \frac{1}{N}\sum_{i=1}^{N} E_i \tag{9}$$

where E_i is the relative error between simulated and observed data, and N is the number of pixels in Northeast China. A smaller RRMSE value represents a higher agreement of these two data and vice versa. RRMSE was also calculated between the air temperature data of each GCM and of ERA5 for the period 2006–2019 in Northeast China.

2.3.5. Calculations of cultivated land productivity

NDVI can be used to reflect the vegetation growth status for large areas in a cost-effective and highly accessible way; therefore, it is widely used to dynamically monitor vegetation change and explore the influence of human activities and changing climate (Cao et al., 2018; Liu et al., 2020). As paddy rice fields generally occupied large areas in Northeast China, the mixed pixel problem caused by 500-m NDVI data sounds trivial in this study and therefore is not considered. Accumulated NDVI is considered as a proxy indicator of cultivated land productivity, avoiding the uncertainty caused by the NDVI conversion to Net Primary Productivity (NPP) (Fang et al., 2007; Liu et al., 2015). Accumulated NDVI is calculated using the following formula:

$$N_r = \sum_{i=SDT10}^{EDT10} NDVI_i / A \tag{10}$$

where N_r is the accumulated NDVI in per-unit cultivated area, A is the cultivated area of each pixel. SDT10 is the starting date with the $\overline{T} \geq 10^{\circ}C$ and EDT10 is the ending date with the $\overline{T} \geq 10^{\circ}C$; the determination of SDT10 and EDT10 is described by (Liu et al., 2021). In this study, the average accumulated NDVI in 2000–2018 was derived to indicate cultivated land productivity in Northeast China.

3. Results

3.1. Spatial-temporal patterns of paddy field change in Northeast China

Increased paddy area in Heilongjiang Province was the major contributor to the total increased paddy area in Northeast China, which was consistent with previous research (Liu et al., 2005). The spatial-temporal patterns of paddy fields in Northeast China during 1990–2018 is shown in Fig. 2. The loss paddy fields were generally distributed in Shenyang City, Liaoning Province, as the result of rapid urban sprawl, infrastructure and industrial development (Fig. 2a). New paddy fields were mainly concentrated in Heilongjiang Province and SongLiao Plain (Fig. 2a). As shown in Table 1, the net paddy planted area in Northeast China ranged from 37000 km^2 in 1990 to 63000 km^2 in 2018, with an increase of 26000 km^2. Paddy fields of Heilongjiang and Jilin Province increased by 29000 km^2 and 2000 km^2 respectively, while those of Liaoning Province decreased by 5000 km^2 during 1990–2018. In combination with the results from Gao and Liu (2011), the increased paddy area was about 40065 km^2 in Heilongjiang Province for the period 1958–2018, of which 18461 km^2 expansion during 1958–2000 and 21604 km^2 expansion during 2000–2018. Meanwhile, the expansion rate of paddy area was 504km^2/a, 369km^2/a (Gao & Liu, 2011) and 1137km^2/a during 1958–1980, 1980–2000 and 2000–2018, respectively.

Table 1 indicates that paddy fields expanded dramatically by nearly two -folds during the past 29 years, and the scale of expansion during 2010–2018 was faster than in the two decades before (1990s and 2000s). During the periods of 1990–2000, 2000–2010 and 2010–2018, the net increase of paddy area was 7000 km^2, 3000 km^2 and 16000 km^2, respectively. Approximately 25800 km^2, 6700 km^2, 4000 km^2 and 2800 km^2 of dry fields, unused land, grassland and woodland were converted into paddy fields during the period of 1990–2018 in Northeast China. Dry fields, unused land, grassland and woodland became the majority contributor to new paddy fields, which occupied 61.8%, 16.0%, 9.5% and 6.8%, respectively (Fig. 2c). Dry fields, the most important source of newly claimed paddy fields, individually contributed to 9827 km^2 (73.53%), 13449 km^2 (71.63%), 15697 km^2 (71.17%) in each decade from 1990 to 2018 (Table 2). Additionally, the second-largest source was unused land, which contributed to 1924 km^2 (14.40%), 1892 km^2 (10.08%) and 2972 km^2 (13.47%) in each decade, respectively. Grassland and woodland were also contributor to new paddy fields during 1990–2018, especially in the Sanjiang Plain of Heilongjiang Province, where the paddy expansion likely resulted from agricultural policies, market demands and agricultural technology improvements.

Considering the large paddy expansion in Northeast China since 2000, quality differences between continuously cultivated paddy fields and newly cultivated paddy fields are illustrated in Fig. 3. Indicators used to evaluate the quality of paddy fields included annual temperature (Tmp), average temperature of early growing season (4-5Tmp), productivity of paddy fields (Productivity), soil organic matter (SOM), DEM, annual precipitation (Pre), distance to river (Dis. River) and distance to roads (Dis. Road). There was little difference between the cultivated land productivity of new paddy fields and continuous paddy fields (mean difference = 0.68, $p < 0.01$); the lower temperature of newly cultivated paddy fields in the entire growing duration and early growing season, with an average temperature difference of −1.85 °C ($p < 0.01$) and −1.38 °C ($p < 0.01$), would increase paddy cultivation costs and raise the risk of frost. Regarding the distance to rivers and roads, the

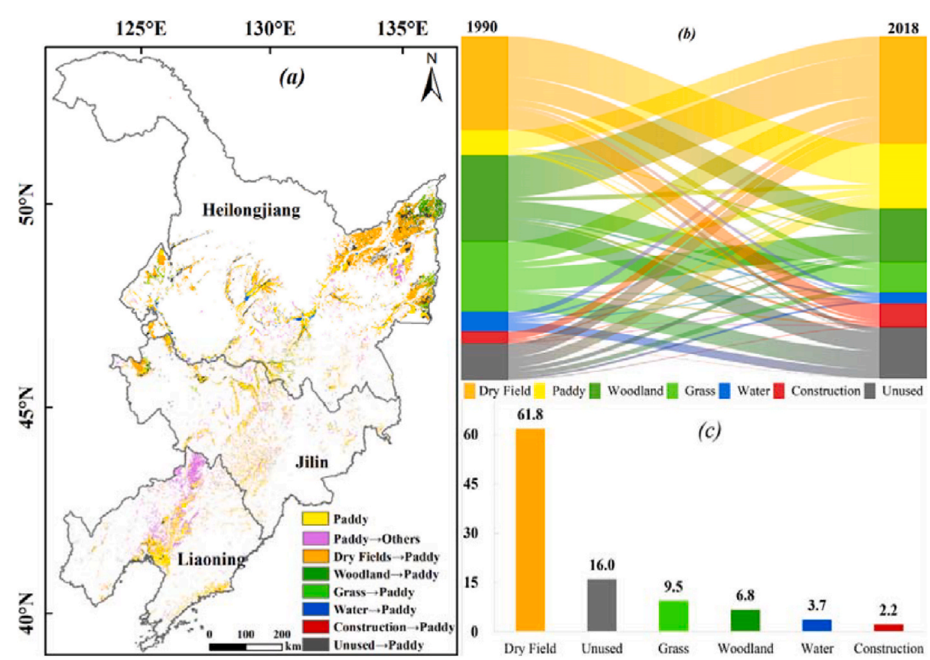

Fig. 2. Paddy field change in Northeast China during 1990–2018. (a) expansion and loss of paddy fields; (b) the LUCC in Northeast China during 1990–2018; (c) proportion of different land use types converted to paddy fields.

Table 1
Land cover and land change during three periods (unit: 10^4 km^2).

Land cover	1990	2000	Changes in 1990–2000	2010	Changes in 2000–2010	2018	Changes in 2010–2018	Changes in 1990–2018
Paddy fields	3.7	4.4	0.7	4.7	0.3	6.3	1.6	2.6
Dry fields	23.9	25.6	1.7	25.3	−0.3	24.8	−0.5	0.8
Woodland	35.9	34.9	−1.0	34.1	−0.8	33.8	−0.2	−2.1
Grassland	5.9	4.9	−1.0	4.8	−0.1	3.3	−1.5	−2.6
Water	2.5	2.4	−0.1	2.2	−0.2	1.9	−0.3	−0.6
Construction land	2.3	2.4	0.1	2.8	0.4	3.1	0.3	0.8
Unused land	4.6	4.2	−0.4	5.0	0.8	5.5	0.5	0.9

Table 2
Source land covers of new paddy fields in 2000, 2010 and 2018.

Land cover	2000		2010		2018	
	km^2	%	km^2	%	km^2	%
Dry fields	9827	73.53	13449	71.63	15697	71.17
Woodland	249	1.87	1268	6.75	485	2.20
Grassland	1194	8.93	688	3.66	1668	7.56
Water	164	1.23	607	3.23	925	4.19
Construction land	6	0.04	873	4.65	309	1.40
Unused land	1924	14.40	1892	10.08	2972	13.47
Sum	13363	100	18780	100	22057	100

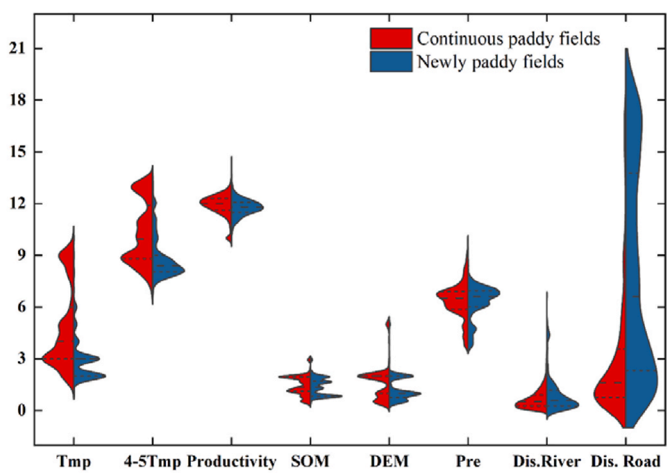

Fig. 3. Quality comparison between continuously cultivated paddy fields (red) and newly cultivated paddy fields (blue) during 2000–2018. (The DEM was shrunk by 10 times, precipitation by 100 times, distance to river and distance to roads by 10000 times to compare each variable directly). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

mean difference between newly cultivated paddy fields and continuously cultivated paddy fields were 48.4 km ($p < 0.01$) and 2.3 km ($p < 0.01$), respectively. Farther distances simultaneously reduced irrigation convenience and transportation effectiveness. Comprehensively, continuously cultivated paddy fields were more likely to have more suitable natural conditions and better infrastructure compared to newly cultivated paddy fields.

3.2. Tendency of the thermal condition distribution in Northeast China

Most regions of Northeast China have been experiencing a warming trend since 1982. Fig. 4a illustrates that 87.7% the mean air temperature of the growing season (April–October) in the entire Northeast China presented significantly increased trends of 0.2–0.5 °C/decade ($p < 0.05$) during the period 1982–2019; 12.3% of annual temperature showed non-significantly increased trends ($p > 0.05$). Stronger warming regions were primarily scattered in the Songliao Plain and the northernmost part of Heilongjiang Province. Annual rice-growing season temperature presented a rising trend of more than 0.25 °C/decade ($p < 0.05$) in entire Northeast China, Heilongjiang, Jilin and Liaoning Province from 1982 to 2019 (Fig. 4b–c). However, the sharply rising temperature during 2007–2008 was followed by climate hiatus around 2010 in Northeast China (Gu, 2007). Additionally, the average temperature dropped by 0.06 °C for the period of 2010–2019, while the average rice-growing season temperature remained basically unchanged in the same period (refer to Fig. 4b–c).

The 0 °C isotherm substantially moved northward from 47°N to 52°N in Northeast China for the period of 1961–2019. Comprehensively considering the results derived from Gao and Liu (2011), the 0 °C isotherm moved northward by 460.5 km over the past 60 years, in which 270 km during 1961–2000 and 190.5 km during 2000–2019. Meanwhile, the 0 °C isotherm moved westward by 428.38 km, including 328.48 km during 1961–2000 and 99.9 km during 2000–2019. Additionally, the 0 °C isotherm expanded by 83108.7 km^2 for the period 1961–2019, and moved northwest by 62129 km^2 and 20979.9 km^2 in 1961–2000 and 2000–2019, respectively (Table 3).

Although the movement direction of the 0 °C isotherm changed under the impact of annual temperature fluctuations, the 0 °C isotherm still shifted remarkably to the northwest by 20979.8 km^2 for the period 2000–2019. The annual temperature of Northeast China generally ranged from −2 °C to 8 °C, except for the emergence of the 10 °C isotherm in 2015–2019 due to climate warming (Fig. 5). The 0 °C isotherm substantially expanded northwestward by 23079 km^2 in 2000–2009 because of sharp warming around 2007 (Fig. 5a–b and Table 3). However, the 0 °C isotherm obviously withdrew southeastward by 21271 km^2 during 2000–2014 due to decreasing annual temperature in 2010–2014 (Fig. 5b–c and Table 3). Subsequently, the warming trend pushed the 0 °C isotherm northwestward by 19172 km^2 again from 2015 to 2019 (Fig. 5c–d and Table 3). Meanwhile, climate warming caused the emergence of the 10 °C isotherm in the southwestern part of Northeast China for the period of 2015–2019 (Fig. 5d).

3.3. Paddy field expansion and climate warming in Northeast China

Temperature was one of the most important factors affecting paddy field production and growth (Gao & Liu, 2011; Tao et al., 2013). As illustrated in Fig. 6, a gradually increasing temperature during the growing season (April–October) explained approximately 55% ($p < 0.01$) of paddy expansion in Northeast China during 1990–2019; similarly, paddy expansion in Heilongjiang Province had a strong linear relationship with a warming trend during the growing season ($R^2 = 0.6$, $p < 0.01$). The timely response of increased paddy area to climate warming could be attribute to the warmer growing condition providing a more suitable environment for paddy growth.

Furthermore, the spatial relationship between paddy field distribution and annual temperature during 1990–2019 is illustrated in Fig. 5. Most paddy fields were confined within the regions above the 2 °C isotherm in the past three decades. As a result of climate warming, paddy fields showed various degrees of expansion over Songliao Plain and Sanjiang Plain in 2000. Scattered paddy fields even appeared between the isotherms of 0 °C and 2 °C. In spite of the southward shift of the isotherm in 2010–2014, paddy fields continuously expanded

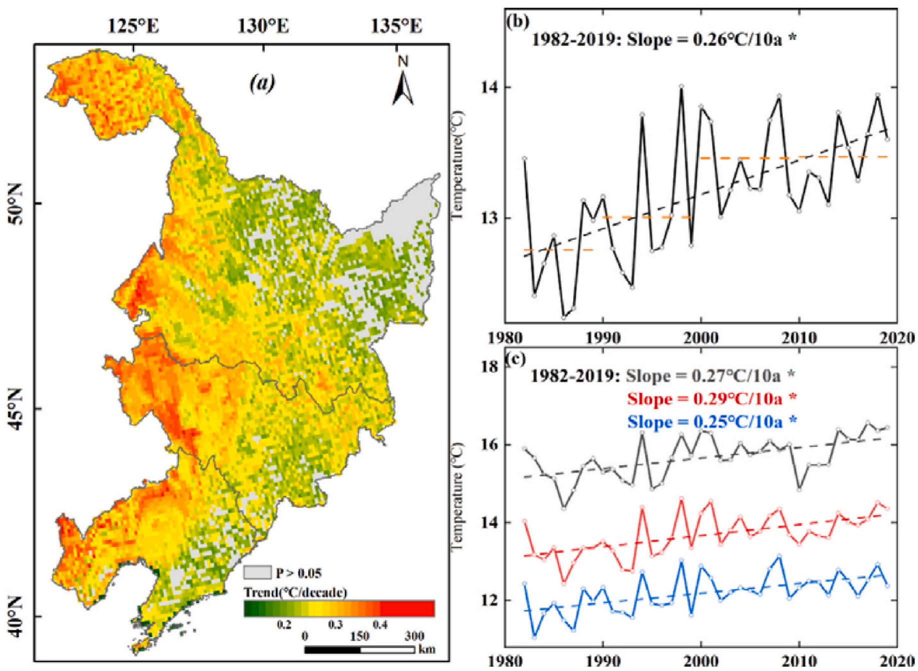

Fig. 4. Spatial pattern of climate warming in Northeast China during 1982–2019. (a) spatial trend of mean air temperature in the growing season (April–October); (b) and (c) rice-growing season temperature trends for Northeast China, Heilongjiang, Jilin and Liaoning Province, respectively. The symbol * indicates the significance at the 0.05 level. The orange dashed lines represent the average of each decade, the black dashed line, the blue dashed line, the red dashed line and the grey dashed line separately represent the trend of rice-growing season temperature in Northeast China, Heilongjiang, Jilin and Liaoning Province during 1982–2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
The movements of the 0 °C isotherm over Northeast China.

Period	Northward shift of the 0 °C isotherm (km)	Westward shift of the 0 °C isotherm (km)	Area of the 0 °C isotherm shift (km^2)
1961–2000	*270*★	*328.48*★	*62129*★
2000–2009	205.1	133.2	23078.6
2010–2014	−197.8	−77.7	−21270.5
2015–2019	183.2	44.4	19171.6
1961–2019	460.5	428.38	83108.7

Note: The symbol ★ represents the results derived from Gao and Liu (2011).

northeastward, especially in Sanjiang Plain. Since the 2 °C isotherm shifted northward again in 2015–2019, paddy fields enlarged northeastward accordingly. The massive expansion of paddy fields since 2010 might be attributed to both climate warming and socio-economic factors.

The barycenter relocation of paddy fields reflected spatial shift directions of paddy production in the overall period (Wang et al., 2018). For the period of 1990–2018, the barycenter of paddy fields continuously moved towards northeast by 312.6 km (Fig. 7). The barycenter of the paddy fields moved northeastward by 81.3 km, 117.6 km and 113.7 km in each decade, respectively. The barycenter of the paddy fields moved across the border of Jilin Province and Heilongjiang Province in 2010, and finally reached the southern Heilongjiang Province in 2018. Furthermore, despite the annual temperature isotherm of Northeast China fluctuating during 2000–2019 (Fig. 7), the 0 °C isotherm still moved northward by 190.5 km and westward by 99.9 km from 2000 to 2019 (Table 3). As the baseline temperature in Heilongjiang Province was lower than that in Northeast China, a tiny increased in temperature would likely have a larger effect on paddy fields production in Heilongjiang Province (Zhang et al., 2019). Increasing temperature provided suitable climate condition for paddy field growth, simultaneously under the influence of market demand and agricultural policies, paddy fields experienced significant expansion in Sanjiang Plain since 2000.

4. Discussion

4.1. Analyses of increasing temperature contributing to paddy field expansion

Temperature plays a crucial role in paddy growth and development in cold region, especially during the reproductive period (Tao et al., 2013; Dong et al., 2015; Zhang et al., 2019; Chen et al., 2020; Liu et al., 2020). As shown in Fig. 4b–c and Fig. 5, rice-growing season temperature and annual temperature in Northeast China presented an increasing trend during 1982–2019; meanwhile, paddy field expansion was related to the isotherm migration trajectory (Gao & Liu, 2011; Liu et al., 2015), especially in Sanjiang Plain of Heilongjiang Province. Climatic warming provided basic thermal conditions for rice growth in regions with low rice-growing season temperature and resulted in more favorable conditions for potential paddy expansion in Northeast China (Liu et al., 2020; Zhang et al., 2019).

However, temperature abruptly increased during 2007–2008 in Northeast China, coupled with climate hiatus in 2000–2014 (Li et al., 2015), resulting in the southeastward withdrawal of the 0 °C isotherm during 2010–2014 (Fig. 7), while paddy fields continued to expand in the mid-high latitude regions of Northeast China since 2010. The possible reasons for the paddy expansion were increasing market demand, agricultural polies implement, improved agricultural technology and management (Dong et al., 2016; Xin et al., 2020). Furthermore, a temporal delay existed between increasing temperature and paddy rice adaptation (Gao & Liu, 2011).

4.2. Analyses of socioeconomic factors contributing to paddy field expansion

Paddy production is complex and driven by various natural and anthropogenic factors. Improved agricultural technologies and physical inputs were major driving factors of the dramatic paddy expansion in Northeast China (Dong et al., 2016; Hu et al., 2019). The results show that the total power of agricultural machinery strongly contributed to paddy rice expansion in Northeast China (R^2 = 0.96, $p < 0.01$) and Heilongjiang Province (R^2 = 0.95, $p < 0.01$) (Fig. 8b and Fig. 8d). Moreover, greenhouse nursery technology provides an important

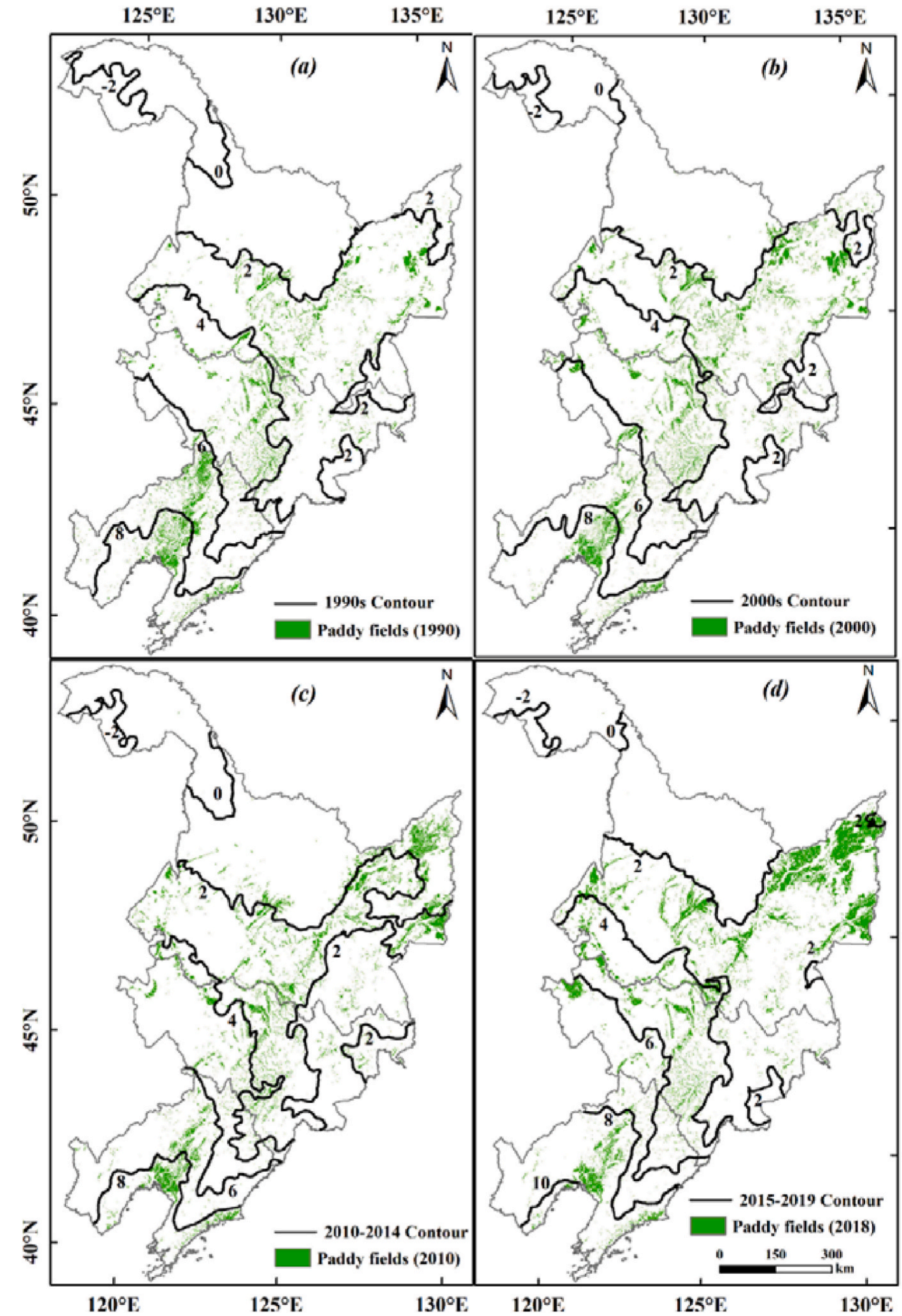

Fig. 5. Temperature distribution and its spatial relationship with paddy field change (a) 1990s, (b) 2000s, (c) 2010–2014 and (d) 2015–2019.

artificial warming approach that prevents paddy fields from frost damage in cold regions. Greenhouse film consumption was used as a proxy for the application of greenhouse nursery technology, Fig. 8b and d illustrate that the paddy field area is significantly related to the amount of greenhouse film consumption during 1990–2019 in Northeast China ($R^2 = 0.94$, $p < 0.01$) and Heilongjiang Province ($R^2 = 0.84$, $p < 0.01$). Meanwhile, optimized paddy cultivars would effectively improve cold-resistant ability and prolong growth duration (Song et al., 2015; Tao et al., 2013).

Furthermore, Fig. 8a and c present a significant correlation between paddy area and the annual producer price of rice in Northeast China ($R^2 = 0.75$, $p < 0.01$) and Heilongjiang Province ($R^2 = 0.79$, $p < 0.01$). The 1-year lag producer price of rice further separately explained about 77% and 82% paddy expansion in Northeast China and Heilongjiang Province during 1991–2018. A reduction in paddy price in 2002 was followed by a paddy planting area reduction in 2003 (Fig. 8a and c). This indicated that farmers' willingness to cultivate paddy rice was largely influenced by market prices, which was consistent with previous studies (Dong et al., 2016; Yu et al., 2014). Moreover, Northeast rice is popular among consumers because of its chewiness, and the purchase price of Northeast rice was generally 5% higher than the national rice purchase price during 2017–2020 (Rice purchase price was derived from the National Food and Strategic Reserves Administration (http://www.lswz.gov.cn/).

Besides, market demands and agricultural policies were also important drivers of paddy field expansion in Northeast China. As shown in Fig. 8b and d, the increasing national urban population was highly correlated with cultivated paddy area expansion in Northeast China ($R^2 = 0.95$, $p < 0.01$) and Heilongjiang Province ($R^2 = 0.94$, $p < 0.01$). Large amounts of cropland converted to construction land in southern

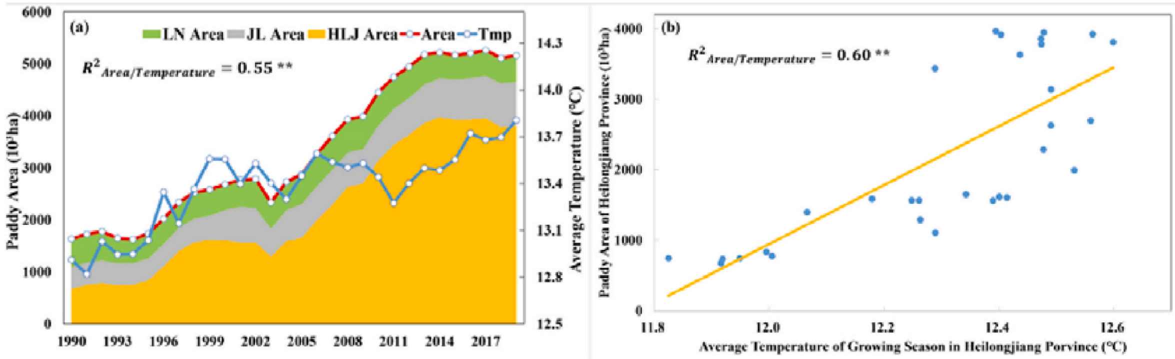

Fig. 6. Climate warming effects on paddy area change. (a) interannual variations of paddy area and mean air temperature in the growing season (April–October) during 1990–2019 over Northeast China. The green, grey and yellow regions represent the paddy area in Liaoning, Jilin and Heilongjiang Province, respectively. (b) relationship between average temperature of growing season and paddy area in Heilongjiang Province from 1990 to 2019. The symbol ** indicates the significance at the 0.01 level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

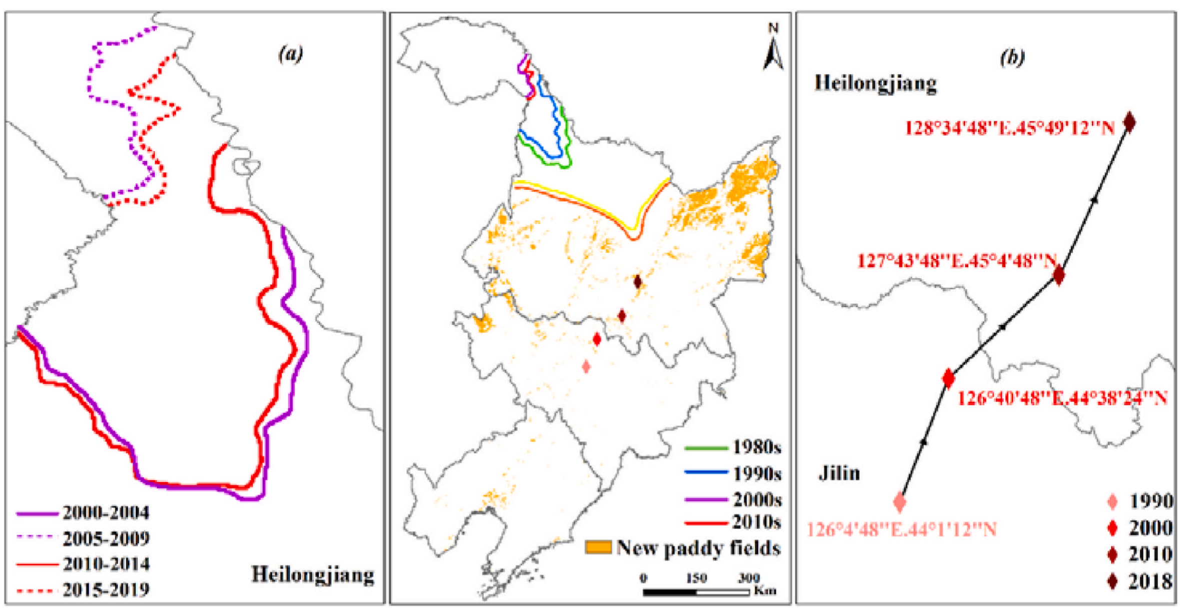

Fig. 7. Northward migration of the 0 °C isotherm from the 1980s to the 2010s and the barycenter relocation of paddy fields in Northeast China during 1990–2018. The orange region represents the newly cultivated paddy fields during 1990–2018. (a) 0 °C isotherm movement at five-year intervals from 2000 to 2019. (b) enlarged barycenter relocation of paddy fields (red dots) during 1990–2018. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

China as a result of urbanization and industrialization progress (Cui et al., 2019; Qiu et al., 2020). Therefore, substantial paddy field expansion over Northeast China was vital to ensure China self-sufficiency in grain production. Meanwhile, a series of agricultural policies were implemented to encourage farmers to cultivate rice. The Chinese government improved the agricultural subsidy policy in 2004 and was exempted from the agricultural tax policy in 2006. Additionally, an agricultural structural adjustment policy was carried out in Heilongjiang Province for the period 1989–2002 by cultivating paddy rice for flood management; subsequently, the High-standard Farmland Construction Project and Two rivers and One Lake Project were implemented to enhance cultivated land quality since 2010 in Heilongjiang Province (Zhang & Song, 2019). Various agricultural policies mobilized farmers' enthusiasm and promoted paddy expansion in Northeast China.

As most paddy expansion occurred in Heilongjiang Province (Figs. 5 and 7), here the impact of climate and other socioeconomic factors on paddy field expansion was estimated by utilizing a stepwise multiple regression model. Rice-growing season temperature was selected to represent the climatic factor. Socioeconomic factors, including total power of agricultural machinery, national urban population and producer price, denoted physical input, urbanization and market demand. As paddy fields in Northeast China are all irrigated (Hu et al., 2019), irrigation was not considered in this study. A positive effect was found for total power of agricultural machinery and rice-growing season temperature on paddy field expansion in Heilongjiang Province, which were highly significant ($p < 0.05$) (Tables S1 and S2). Similarly, urban population and producer price were also positively related to paddy expansion in Heilongjiang Province ($p > 0.05$).

4.3. Impacts of future climate change on paddy production

To further explore future climate change on paddy production in Northeast China, future climate data were generated from three GCMs, including MRI-CGCM3, MIROC5 and CanESM2. According to the value of SC and RRMSE, the validation of three GCMs performance is listed in Table 4. All selected GCMs performed satisfactorily with SC over 0.99 and RRMSE around 0.01. A significantly increasing trend of 0.35–0.45 °C/decade ($p < 0.05$) was found across the entire Northeast

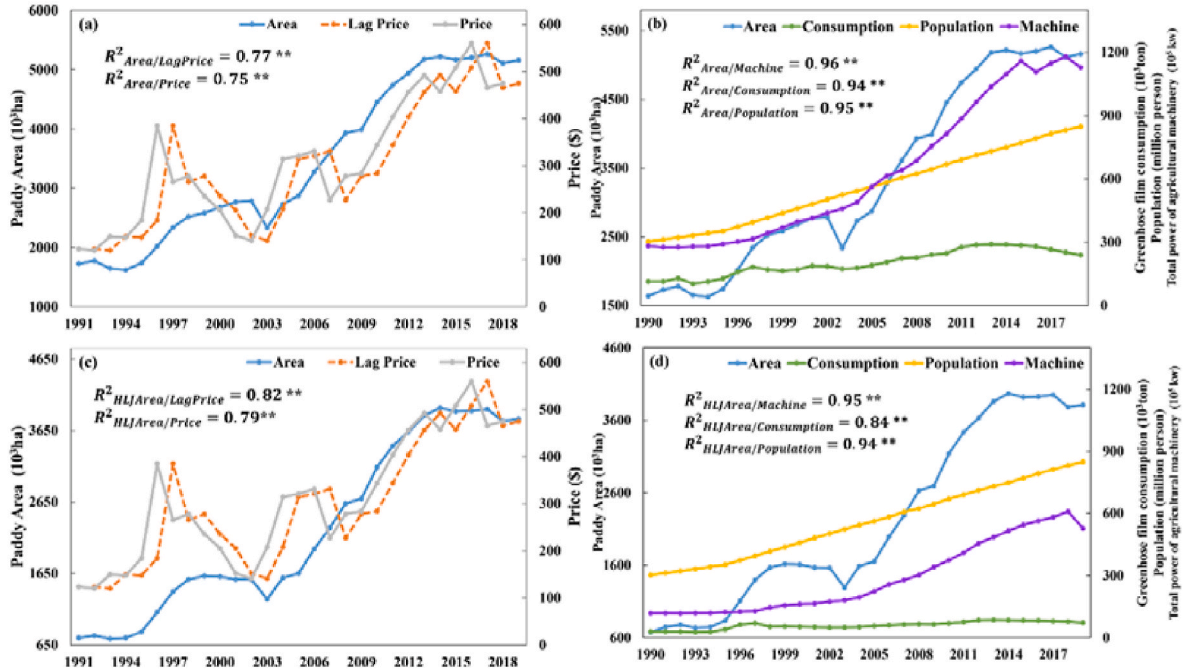

Fig. 8. Interannual variations of paddy area and producer price, greenhouse film consumption, total power of agricultural machinery and national urban population during 1990–2019 in Northeast China (a–b) and Heilongjiang Province (c–d). The orange dashed line shows the 1-year lag of producer price. The symbol ** represents the significance at the 0.01 level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Three selected GCMs performance and resolution.

Model	Institution	Temperature SC	Temperature RRMSE	Resolution
MRI-CGCM3	MRI, Japan	0.998	0.010	320 × 160
MIROC5	MIROC5, Japan	0.998	0.014	256 × 128
CanESM2	CCCMA, Canada	0.999	0.012	128 × 64

China for the period of 2020–2050 (Fig. 9). The simulated rice-growing season temperature with higher increases was found in parts of southeastern Liaoning Province and entire Heilongjiang Province, especially in most regions of Sanjiang Plain and northern Heilongjiang Province; a slighter increase was mainly distributed in the southwestern region of Liaoning Province and western Jilin Province. Predicted rice-growing season temperature presented a rising trend of 0.40 °C/decade ($p < 0.01$), 0.41 °C/decade ($p < 0.01$), 0.38 °C/decade ($p < 0.01$), 0.39 °C/decade ($p < 0.01$) in entire Northeast China, Heilongjiang, Jilin and Liaoning Province during 2020–2050, respectively (Fig. 9b–c).

As various studies indicated that paddy production was strongly affected by climate change (Xia et al., 2014; Wu et al., 2014; Li et al., 2015; Ling et al., 2019; Xin et al., 2020). Fig. 9a illustrates that the 0 °C isotherm is still projected to largely shift northwestward during 2020–2050, almost reaching 53°N in northern Heilongjiang Province by 2050. The increased thermal resource could further expand the potentially suitable region for paddy growth, which would be positive for paddy production in a certain future in Northeast China, especially in Heilongjiang Province (Li et al., 2015; Ling et al., 2019; Wu et al., 2014; Xia et al., 2014; Xin et al., 2020). Moreover, climate warming reduced low-temperature stress to possibly relieve paddy suffering from chilling injury in early growing season (Ling et al., 2019; Liu et al., 2020). Meanwhile, except for the direct effects of a warming climate on paddy growth, indirect effects of rising temperature would partly suppress paddy production, for instance, increasing pests and agro-meteorological disasters (Chen et al., 2020; Piao et al., 2010).

4.4. Implications and suggestions for regional agriculture sustainable development

Driven by climate warming, the regional agricultural structure in Northeast China has undergone significant changes. Following the natural rhythms and economic laws, optimizing soil-water resource allocation and the human-earth relationships would become essential for the sustainable development of modern agriculture over Northeast China (Liu, 2020). Moreover, as smallholder farming dominated the agricultural production in China, the adaptation strategies and cultivation practices of local household farmers would have greatly influence paddy production in Northeast China (Cui et al., 2018). Recent research indicated that selecting paddy rice cultivars and adjusting planting date, rather than disaster prevention and infrastructure improvement, were common adaptation approaches to climate warming in Northeast China, possibly because the former was more easily achieved and less costly than the latter (Yu et al., 2014; Zhao et al., 2019).

Furthermore, intensive utilization of cultivated land and over-fertilizing management in Northeast China inevitably caused declines in the natural fertility of black soil, imbalanced soil nutrient, thinning of the cultivated layer and exacerbated soil erosion (Liu et al., 2006; Han & Li, 2018; Xu et al., 2010). In addition, newly cultivated paddy fields occupied large amounts of swamps and grasslands, which might undermine the protection against storms and floods, and further cause more serious soil erosion in Northeast China (Xu et al., 2010)

Northeast China is a vitally important cultivated land preservation region and commodity grain base in China. Considering the strategy of 'Storing Grain in Land and Technology', the systematic promotion of 'Black Soil' protection and high-standard farmland construction are the core tasks for comprehensively implementing a rural revitalization strategy. Therefore, various agricultural strategies have been proposed to develop sustainable agriculture and safeguard the ecological environment in Northeast China. Firstly, the expansion rate of paddy fields should be slowed down, as a sharp excessive expansion might cause severe ecological issues and further reduce paddy quality and yield (Li et al., 2018 b). Secondly, optimal paddy rice cultivars with improved cold temperature tolerance and longer growth duration, coupled with

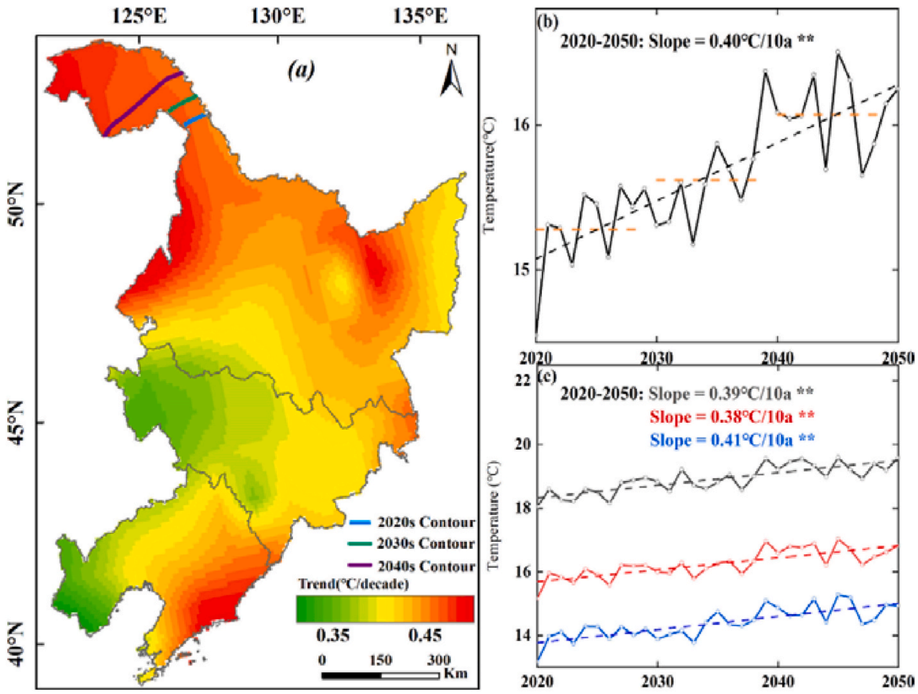

Fig. 9. Spatial pattern of future climate change in Northeast China during 2020–2050. (a) spatial trend of rice-growing season temperature (April–October) and 0 °C isotherm movements during 2020–2050; (b) and (c) trend of rice-growing season temperature related to Northeast China, Heilongjiang, Jilin and Liaoning Province, respectively. The symbol ** represents the significance at the 0.01 level. The orange dashed lines in (b) represent the average of each decade, the black dashed line, the blue dashed line, the red dashed line and the grey dashed line separately represent the trend of rice-growing season temperature in Northeast China, Heilongjiang, Jilin and Liaoning Province during 2020–2050. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

suitable agronomic practices probably would boost paddy yield and grain production in Northeast China (Chen et al., 2020; Tao et al., 2013; Zhao et al., 2019). Thirdly, local governments need to fully mobilize farmers' initiatives and enable leading farmers to guide other farmers to prepare for disaster prevention awareness and empower them with advanced agricultural technique (Cui et al., 2018; Wu et al., 2014). Additionally, if Chinese national government builds a long-term mechanism with improved agricultural policies, enhanced infrastructure construction and agricultural structure adjustment, grain production might increase as well as farmers income (Cheng et al., 2006; Zhang et al., 2020). Finally, a robust rice system, which balances potential benefits against risks and comprehensively considers actual agricultural production and ecological environment, is urged to establish sustainable rice production in Northeast China (Zhang et al., 2019). In addition, the importance of the double rice cropping system in southern China should not be neglected in view of the more suitable natural growing conditions and indispensable position for bolstering food security in China (Chen et al., 2020; Liu et al., 2020).

5. Conclusions

This study first investigated the spatial-temporal patterns of paddy fields in Northeast China for the period of 1990–2018 and linked it with previous studies; further, it compared the quality differences between newly cultivated and continuously cultivated paddy fields; finally, it analyzed the response of paddy field changes to climate warming and socioeconomic driving factors, and attempted to provide some potential suggestions for sustainable agriculture development in Northeast China. Results indicated that the 0 °C isotherm moved northward by 460.5 km for the period 1961–2019, in which 270 km during 1961–2000 and 190.5 km during 2000–2019. Net paddy areas expanded by 26000 km^2 in Northeast China during 1990–2018; in particular, paddy fields in Heilongjiang Province expanded dramatically by about 18461 km^2 during 1958–2000 and 21604 km^2 during 2000–2018, respectively. However, continuously cultivated paddy fields generally had more suitable thermal conditions and better geographic location than new paddy fields. In addition to the effects of warming climate, agricultural policy implementations, increasing market demands, improved agricultural technologies and management could be largely responsible for obvious paddy field expansion towards relatively higher latitude regions in Northeast China. Some potential suggestions were proposed for sustainable agricultural development in Northeast China. Although feeding an increasing population is a difficult challenge, the findings of this study show that this goal can be achieved with the concerted efforts of the government and smallholder farmers. Additionally, gathering more data, information and model simulation on other driving factors, such as black soil use and paddy yield predictions in Northeast China, will be helpful for improving our knowledge and proposing more comprehensive suggestions for sustainable agricultural development.

Credit author statement

Yansui Liu: Conceptualization, Supervision, Funding acquisition, Writing and editing manuscript; Xueqi Liu: Conceptualization, Data Resource, Methodology, Software, Writing manuscript; Zhengjia Liu: Supervision, Editing manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2022.102667.

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