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Impact of cropland use changes based on non-agriculturalization, non-grainization and abandonment on grain potential production in Northeast China

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Cropland is the basic resource and condition for human survival. However, since 2000, Northeast China has been faced with severe challenges to grain production caused by non-agriculturalization, non-grainization and cropland abandonment, which in turn pose a potential threat to the long-term food security of the whole region and even China. This paper used GIS spatial analysis and statistical analysis methods to explore the impacts of non-agriculturalization, non-grainization and cropland abandonment on grain potential production (GPP) in Northeast China at a grid scale. From 2000 to 2020, the cropland area of Northeast China increased by about 2.10% (9,275.51 km²), and the gravity center of cropland moved to the northeast with a moving distance of 9.18 km. The total lost GPP in Northeast China was $1{,}410.16 \times 10^4$ tonnes due to the non-agriculturalization, non-grainization and abandonment of cropland. Cropland abandonment was the main type of cropland use change leading to the loss of GPP. The dominant type of cropland use change was different in different provinces (regions), leading to different degrees of GPP loss. Heilongjiang Province and Inner Mongolia were dominated by cropland abandonment. Jilin Province and Liaoning province were mainly non-agriculturalization. At the same time, the conversion of cropland to orchards was more common in southern Liaoning Province. Since 2000, the proportion of sown area for grain crops in Northeast China and other provinces (regions) has increased, resulting in an increase of $1{,}134.76 \times 10^4$ tonnes in GPP, which has made up for the loss of GPP caused by other cropland use changes to a certain extent. In the future, measures should be taken to protect cropland, such as restoring agricultural production on abandoned cropland as soon as possible, strengthening the input and policy support of modern agricultural production factors in main grain producing areas, constructing the elastic mechanism of grain production-farmland fallow conversion, improving the intensive utilization rate of urban and rural land, perfecting the balance system of cultivated land occupation and compensation, and perfecting the land circulation mechanism.

Keywords Cropland use change, Non-agriculturalization, Non-grainization, Cropland abandonment, Grain potential production (GPP), Northeast China

Food security is an important guarantee for world peace and development, an important foundation for building a community with a shared future for mankind, and bears on the sustainable development, future and destiny of mankind. The latest Global Report on Food Crises (GRFC) shows that nearly 282 million people in 59 countries and territories are facing acute hunger in 2023. That's 24 million more than the previous year. At the same time, only about one-third of the global population's needs are met by local food crop production, and two-thirds are highly dependent on food shipments[1]. In recent years, with the impact of extreme weather, the 2019 COVID-19 pandemic and intensifying regional conflicts, ensuring regional food self-sufficiency will become even more critical[2,3]. China occupies about 9% of the world's cropland, ranking third after the United States and India, and is therefore duty-bound to support global food production. With a vast land area, fertile soil, concentrated and contiguous cropland, rich climate resources, and huge potential for grain production, Northeast China is an

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important main grain producing area and commercial grain production base in China[4]. On September 7, 2023, General Secretary Xi Jinping clearly pointed out at the Symposium on Promoting Comprehensive Revitalization of Northeast China in the New Era that "it is the primary responsibility of Northeast China to be the 'ballast stone' of the country's stable food production and supply".

However, with the current rapid economic growth, the process of urbanization is accelerating, which is a great threat to food security[5]. Urbanization is considered to be a process of transformation from a rural society based on agriculture to an urban society based on industry[6]. This shift often leads to the occupation of cropland for urban development[7]. Therefore, urbanization is always accompanied by the reduction of cropland, leading to cropland non-agriculturalization[8]. In the past few decades, the expansion speed and intensity of built-up land in Northeast China have increased significantly, which has led to the loss of a large number of high-quality cropland around the region. For example, from 1990 to 2019, the cropland occupied by built-up land expansion in the central corn belt of Jilin Province reached 517.72 km^2 and mainly occupied the cropland on the outer edge of the urban region[9]. In addition to the occupation of cropland by built-up land, a serious problem facing China at present is that the phenomenon of planting cash crops in cropland and converting cropland into orchards is increasingly common due to factors such as economic efficiency, the number of labor forces, scientific and technological progress, and agricultural policies. For Northeast China, under the support of cropland protection policies such as "black soil granaries" in recent years, the proportion of sown area of grain crops has increased year by year, almost reaching more than 80%, but the phenomenon of converting cropland to orchards is still common[4]. In addition, affected by land contracting policies, low economic benefits, and labor outflow, the phenomenon of cropland abandonment in Northeast China has been relatively serious in recent years. Under the influence of cropland use changes such as non-agriculturalization, non-grainization and abandonment, the trend of "quantity and quality reduction" of cropland resources in Northeast China, as a major grain producing area, has become increasingly prominent[10] which seriously threatens food security.

In order to cope with the challenges of the above changes in the cropland use to grain production, The State Council and the Ministry of Agriculture and Rural Affairs have successively issued a series of policy documents, such as Opinions on Preventing the "Non-grain Cultivation" of Cropland and Stabilizing Grain Production, Opinions on Strengthening the Protection of Cropland and Improving the Balance of cropland quality, and Action Plan for Conservation Farming of Black Land in Northeast China (2020–2025). With the support of the above policies, although some progress has been made in the cropland protection in Northeast China, the above problems are still widespread. There is therefore an urgent need to clarify the threat to grain production posed by cropland use changes[11].

So far, scholars have carried out a lot of research on the impacts of cropland use changes on grain production[12–15]. For example, Jiang explored the impacts of the internal use structure transformation of cropland and the conversion between cropland and other land types on cropland productivity in Heilongjiang Province from 2000 to 2015[13]. Zhao et al. analyzed the correlation between cropland area changes and grain productivity changes at the provincial and prefectural levels in China from 2009 to 2016, and further evaluated the contributions of conserved cropland (grain yield and multiple cropping index) and extended cropland (proportion of sown area of grain crops) to grain productivity respectively[14]. As for different types of cropland use changes, there have been a lot of studies on non-agriculturalization, non-grainization and abandonment. The study of Yang et al. revealed that from 1990 to 2000, the non-agricultural cropland area in the urban agglomeration of central Yunnan Province increased by 6.88×10^3 hm^2 on average annually, and decreased by 2.66×10^4 hm^2 on average annually after 2000[16]. From 1980 to 2020, the cropland area for non-agricultural use in Heilongjiang Province increased in general, but the changes were various in different periods[17]. In 2020, the non-grainization rate of cropland in China was about 27%, with large differences among different regions, but not obvious in Northeast China, which was only about 7%[18]. In 2017, the rates of cropland abandonment in Liaoning, Jilin and Heilongjiang were 3.38%, 2.83% and 3.60% respectively, and even as high as 6.87% in Inner Mongolia[19,20]. However, most of the previous studies focus on the spatio-temporal evolution characteristics, driving factors and management strategies of cropland non-agriculturalization, non-grainization and abandonment, but their threats to grain production have not been fully elucidated. In addition, previous studies mainly focused on a single type of cropland use changes, lacking comprehensive evaluation and systematic calculation of the impacts of multiple cropland use changes on grain production. Therefore, the highlights of this study are, (1) to systematically evaluate the combined impacts of multiple cropland use changes (non-agriculturalization, non-grainization, abandonment) on grain potential production (GPP); (2) to explicitly measure the threats of cropland loss and misuse to GPP, filling a critical gap in current research; and (3) to reveal varying impacts across regions, supporting tailored policies for sustainable cropland management. Further clarifying the impacts and spatial heterogeneity of various cropland use changes on grain production in Northeast China during the process of economic development can provide powerful guidance for the formulation of cropland management strategies in Northeast China and the exploration of effective ways to increase grain production.

Therefore, aiming at the problems of cropland use in the social and economic development of Northeast China since 2000, this study combined GIS spatial analysis and statistical analysis to comprehensively explore the impacts of changes in three specific aspects of cropland non-agriculturalization, non-grainization and abandonment on GPP at a grid scale. The main objectives of this study are, (1) to identify the spatio-temporal evolution characteristics of cropland non-agriculturalization, non-grainization, abandonment in Northeast China since 2000; (2) to clarify the combined impacts of multiple cropland use changes on GPP in Northeast China at a grid scale; and (3) to reveal the spatial heterogeneity of these effects.

This results deeply analyzed the trend of cropland use changes in Northeast China in recent decades, optimized the method to quantitatively explore the spatial-temporal heterogeneity of the impacts of different cropland use changes on GPP, and provided reference for exploring effective strategies to improve grain production in Northeast China.

Materials and methods
Study area
Northeast China is located in the northeast of China's mainland, covering 40 prefecture level cities and four provinces including Heilongjiang, Jilin, Liaoning, and the eastern parts of the Inner Mongolia Autonomous Region (IMAR). It extends from 38°40′ N to 53°34′ N, and 115°05′ E to 135°02′ E (Fig. 1). The total land area of Northeast China is about 1.24 million km². It is surrounded by middle and low mountains along three directions, such as the Greater Khingan Mountains in the northwest, the Lesser Khingan Mountains in the northeast, and the Changbai Mountains in the southeast[21]. Three major plains are located in northeast China, with Sanjiang Plain in the northeast corner, Songnen Plain in the middle, and Liaohe Plain in the south[22]. Northeast China is located in the continental monsoon climate area with mild and humid summer and bitter and long winter[23]. The annual average temperature is 5 to 10.6 ℃, and the 10 ℃ annual accumulated temperature is 2200–3600 ℃ from north to south. The annual accumulated precipitation ranges from 1000 mm in the east to 400 mm in the west[24]. The major soil types are brown coniferous soil, dark brown forest soil, forest steppe chernozem, and meadow steppe chernozem[25]. The cropland in Northeast China accounts for about 1/3 of the total area and has great agricultural production potential. The major crops planted in Northeast China include maize, soybean, rice, wheat, millet, and sorghum.

Data sources and preprocessing
The data required for this study comprise the global 30-m land-cover dynamic monitoring product with a fine classification system from 2000 to 2020 (GLC_FCS30), CNLUCC for 2000, 2005, 2010, 2015 and 2020, GPP data in 2000, statistics of grain crops and crop sown area from 2000 to 2020 of Northeast China (Table 1).

GLC_FCS30 of Northeast China from 2000 to 2020 was the land cover dynamic product at a 30-m resolution that adopts continuous change detection[26–28]. The dataset utilizes a refined classification system containing basic
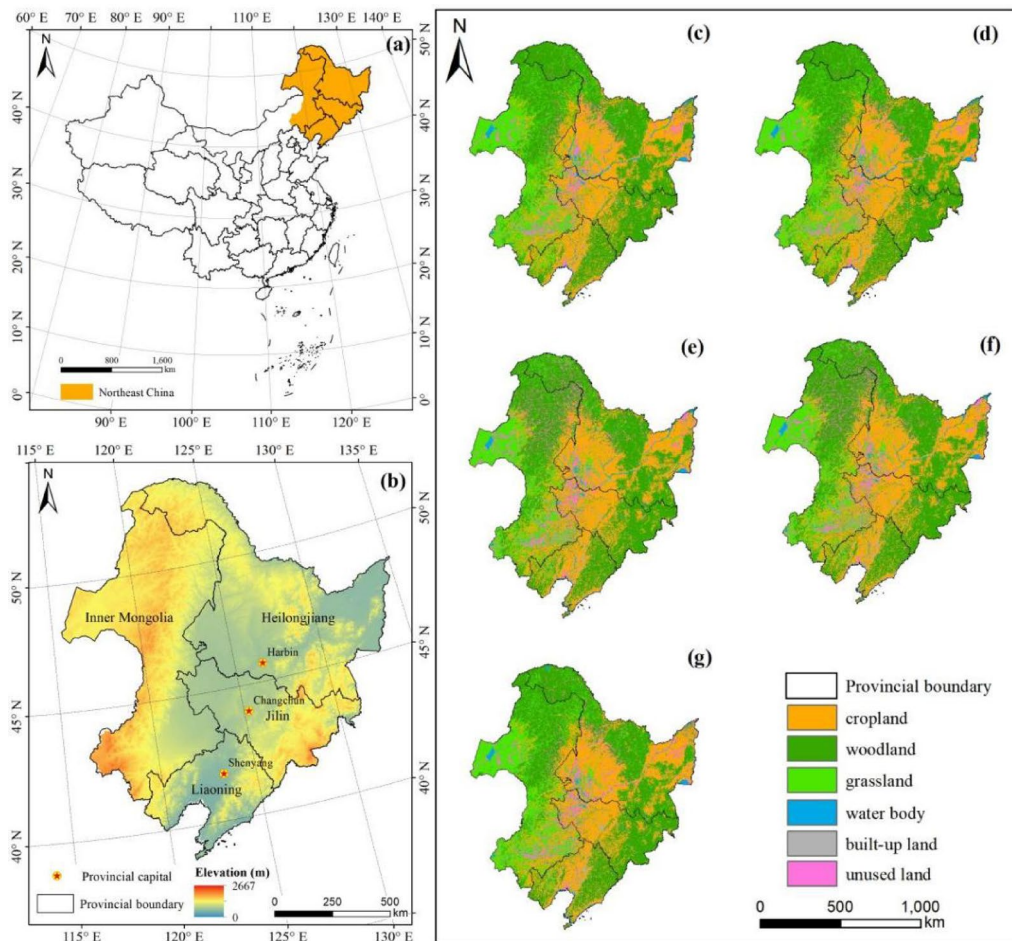
Fig. 1. Location of Northeast China[1,2]. (**a**) China; (**b**) Northeast China; (**c–g**) are the distributions of land use types for 2000, 2005, 2010, 2015 and 2020 derived from the China's Multi-Period Land Use Land Cover Remote Sensing Monitoring Dataset (CNLUCC). [1]The map was based on the standard map No. GS(2024)0650 downloaded from the Standard Map Service website of the Ministry of Natural Resources. The base map has not been modified. [2]The map was created by ArcGIS 10.8 software (https://desktop.arcgis.com/zh-cn/arcmap/index.html).

Dataset	Year	Original spatial resolution	Final spatial resolution	Reference URL
GLC_FCS30	2000–2020	30 m	30 m	https://data.casearth.cn/item/6523adf6819aec0c3a438252
CNLUCC	2000, 2005, 2010, 2015, 2020	30 m	30 m	https://www.resdc.cn/DOI/DOI.aspx?DOIID=54
GPP	2000	1 km	30 m	https://www.resdc.cn/data.aspx?DATAID=261
Statistics of food crops and crop sown area	2000–2020	–	–	–

Table 1. Data sources in this study.
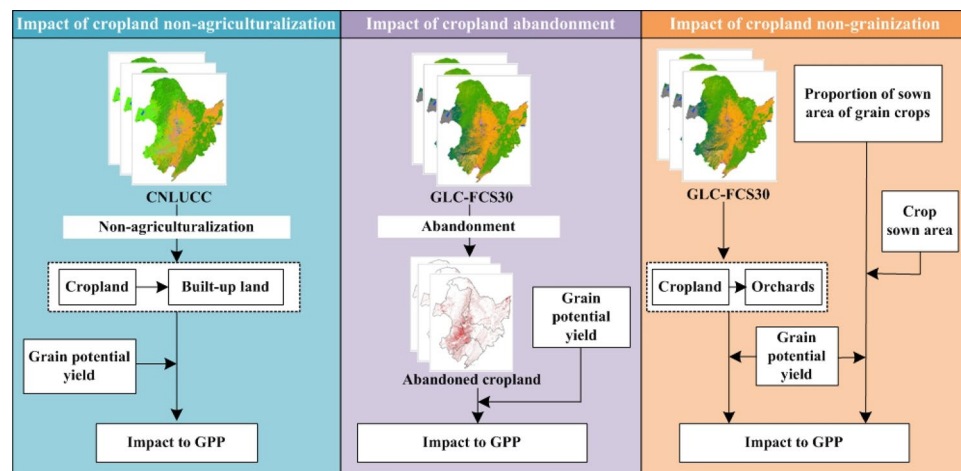
Fig. 2. Flowchart for estimating the impacts of non-agriculturalization, non-grainization, and abandonment on GPP[1]. [1]The map was created by Microsoft Visio 2021 software (https://www.microsoft.com/zh-cn/microsoft-365/visio/flowchart-software).

classification system (including 10 basic land categories), level-1 validation system (including 17 level-1 land categories) and fine classification system (including 35 level-2 land categories).

CNLUCC of Northeast China for 2000, 2005, 2010, 2015, 2020 was constructed based on Landsat MSS, TM/ETM, and Landsat8 satellite remote sensing data using man–machine interactive visual interpretation[29]. It consists of 6 level-1 land categories (cropland, woodland, grassland, water body, built-up land, and unused land) and 25 level-2 land categories.

GPP data of Northeast China in 2000 came from the dataset of cropland potential production in China[30]. The dataset is based on China's cropland distribution, soil and elevation DEM data, adopts the Global Agro-Ecological Zones (GAEZ) model, taking into account various factors such as light, temperature, water, CO_2 concentration, disease and insect pests, agroclimatic restrictions, soil and terrain, and estimates the potential production of cropland in China. It mainly considers five kinds of crops, including wheat, maize, rice, soybean and sweet potato. The GPP data need to apply simple resampling method to change the original spatial resolution of 1 km to 30 m in order to be consistent with the spatial resolution of GLC_FCS30 and CNLUCC data.

Statistics of food crops and crop sown area from 2000 to 2020 derived from the statistics in Statistical Yearbook of Heilongjiang, Jilin, Liaoning and Inner Mongolia from 2001 to 2021.

Methods

In this study, the cropland use changes in Northeast China since 2000 are classified into three types, including non-agriculturalization, non-grainization and abandonment, and their impacts on GPP were systematically analyzed (Fig. 2).

Estimation method for the impact of non-agriculturalization on GPP

The essence of non-agriculturalization of cropland refers to the process of transforming cropland into built-up land. The change trend and direction of non-agricultural cropland reflect the basic trend of social and economic development at present[31]. Based on the CNLUCC dataset, this study identified the regions where the cropland was occupied by the built-up land during 2000–2005, 2005–2010, 2010–2015, 2015–2020, 2000–2020, and estimated the lost GPP due to the non-agriculturalization of cropland during 2000–2020 in Northeast China[32]. The Eq. (1) is as follows[33]:

$$GPP_1 = \sum_{i=1}^{n} S_i \times Y_i \qquad (1)$$

.

while GPP_1 is the lost GPP due to the non-agriculturalization of cropland, S_i is the area of the ith pixel that the cropland converted into the built-up land, Y_i is the grain potential yield in the ith pixel that the cropland converted into the built-up land, $i = 1,2,…,n$. In this study, the spatial resolution of the estimated results of lost GPP was 30 m, which was consistent with the original spatial resolution of CNLUCC dataset, so the S_i was fixed at 900 m^2.

Estimation method for the impact of Non-grainization on GPP

"Opinions on preventing the non-grainization of cropland and stabilizing grain production" believes that the non-grainization of cropland mainly includes two aspects. First, the transformation of cropland into woodland, orchards, pit and pond farming and other types of agricultural land was called the non-grainization of agricultural production structure. Second, the transformation of grain crops into cash crops in the cropland was called the non-grainization of planting structure. Therefore, based on the Statistical Yearbook of four provinces in Northeast China from 2001 to 2021, this study calculated the proportion of grain crop sown area in each province (region) from 2000 to 2020, and then calculated the changes of GPP caused by the changes of the proportion of grain crop sown area during 2000–2020 in Northeast China. Meantime, based on the GLC_FCS30 dataset, this study identified the regions where the cropland was occupied by the orchards (including fruit orchard, mulberry orchard, tea garden, and other types of plantation) during 2000–2005, 2005–2010, 2010–2015, 2015–2020, 2000–2020, and estimated the lost GPP due to the cropland converting into the orchards during 2000–2020 in Northeast China. The reason that we didn't consider the regions that the cropland converted into the woodland was that we can't distinguish whether the woodland in the CNLUCC dataset was artificial or natural forests. Most of the woodland in Northeast China are natural forests, so the cropland converted into the woodland was counted as the abandonment of cropland. The reason that we didn't consider the regions the cropland converted into the pit and pond farming was that we also can't distinguish whether the reservoir and pit were used as the pond farming, so this situation was ignored in this study. The Eqs. (2)-(4) are as follows[33]:

$$GPP_{21} = \sum\nolimits_{j=1}^{4} \Delta R_j \times AACSA_j \times Y_j \tag{2}$$

$$GPP_{22} = \sum\nolimits_{i=1}^{n} A_i \times Y_i \tag{3}$$

$$GPP_2 = GPP_{21} + GPP_{22} \tag{4}$$

.

while GPP_2 is the lost GPP caused by the non-grainization of cropland, GPP_{21} and GPP_{22} represent the changes of GPP due to the changes of the proportion of grain crop sown area and the lost GPP due to the cropland converting into the orchards respectively, $AACSA_j$ is the annual average crop sown area in the jth province (region), Y_j is the average grain potential yield in the jth province (region), $j = 1,2,3,4$, A_i represents the area of the ith pixel that the cropland converted into the orchards, Y_i is the grain potential yield in the ith pixel that the cropland converted into the orchards, $i = 1,2,…,n$. Due to the lack of reliable remote sensing data on the proportion of grain sown, the changes of GPP caused by planting cash crops were estimated by provincial and regional administrative units. Equally, in this study, the spatial resolution of the estimated results of GPP_{22} was 30 m, which was consistent with the original spatial resolution of CNLUCC dataset, so the A_i was fixed at 900 m^2.

Estimation method for the impact of cropland abandonment on GPP

Cropland abandonment refers to the phenomenon that cropland resources stop farming activities under the restriction of natural, social, economic, policy and other factors in rural development, and cropland is vacant or barren[34] which usually refers to the natural succession of idle cropland. In this study, we utilized the definition of "abandoned cropland" as defined by the 2011 International Symposium on Land Consolidation and Land Reserve, that is, cropland that has not been cultivated for more than two consecutive years. Therefore, based on the GLC_FCS30 dataset, we analyzed the land use trajectory of each pixel from 2000 to 2020, and identified the pixels of the land cover categories in which the cropland converted to the natural cover for at least two consecutive years, namely, the abandoned cropland pixels. We counted the area of cropland abandonment year by year in Northeast China from 2002 to 2020, as well as the area change of cropland abandonment, and drew a linear trend line to explore the area change of cropland abandonment. It is worth noting that the abandoned cropland only refers to the land categories in which the cropland converting to the natural cover for two or more consecutive years, and does not include the cropland converting to the impervious surface, water body, permanent glaciers or snow. For the GLC_FCS30 dataset, the non-cropland pixels with codes 190, 150, 152, 153, 200, 201, 202, 210, 220 were not counted. The Eq. (5) is:

$$GPP_3 = \sum\nolimits_{i=1}^{n} AA_i \times Y_i \tag{5}$$

.

while GPP_3 is the lost GPP due to the cropland abandonment, AA_i represents the area of the ith cropland abandoned pixel, Y_i is the grain potential yield of the ith cropland abandoned pixel, $i = 1,2,…,n$. Equally, in this study, the spatial resolution of the estimated results of GPP_3 was 30 m, which was consistent with the original spatial resolution of GLC_FCS30 dataset, so the AA_i was fixed at 900 m^2.

## Results

Spatio-temporal changes of cropland

The changes of cropland area in Northeast China and four provinces (regions) from 2000 to 2020 are shown in Figure S1. The values are the ratios of annual cropland area and multi-year averaged cropland area. In the entire Northeast China, the cropland area increased by approximately 2.10% (9,275.51 km²) from 2000 to 2020. During the period from 2000 to 2008, there was a slight decrease in cropland area (1,274.61 km²). However, from 2008 to 2020, there was a continuous increase (10,550.23 km²). The change trend of cropland area also exhibited significant differences among the four provinces (regions). In Heilongjiang Province, the cropland area showed an almost steady increase from 2000 to 2020 with a total increase of 3.10% (6,013.29 km²). Jilin Province experienced a slight decrease followed by a minor increase in cropland area over the course of 21 years, resulting in an overall increase of about 0.29% (258.17 km²). Conversely, Liaoning Province witnessed an almost continuous decrease in cropland area from 2000 to 2020 with a total reduction of approximately 1.72% (1,241.77 km²). In Inner Mongolia, the cropland area increased almost uniformly over this period by around 3.10% (4,251.17 km²).

In order to further clarify the temporal and spatial characteristics of cropland changes, we drew the shift map of cropland gravity center every five years from 2000 to 2020, as shown in Figure S2. Overall, the cropland gravity center moved northeast from 2000 to 2020, with a distance of 9.18 km. From 2000 to 2015, the cropland gravity center mainly moved northward, with distances of 0.73 km, 6.97 km, and 0.54 km, respectively. From 2015 to 2020, the cropland gravity center mainly moved eastward, with a distance of 5.65 km. Therefore, there was a clear northward trend in the cropland gravity center since 2000, which may be due to the expansion of cropland suitable for planting regions to the north due to climate warming, as well as the acceleration of urbanization in the southern region occupying cropland, resulting in the overall northward movement of cropland.

Impact of Non-agriculturalization on GPP

During 2000–2020, the area undergoing non-agriculturalization in Northeast China totaled 9,176.95 km² corresponding to a non-agriculturalization rate of approximately 2.48%. The majority of these non-agriculturalized regions were concentrated in the eastern and southern regions of Northeast China, particularly in the southwestern part of Heilongjiang Province, central Jilin Province, and most parts of Liaoning Province (Figure S3). Analyzing different time periods reveals that the largest extent of non-agriculturalization occurred between 2005 and 2010, amounting to 6,539.18 km². This was followed by the period from 2015 to 2020 with the area of 4,737.65 km². Conversely, the smallest area of non-agriculturalization took place between 2000 and 2005 at just 569.42 km². Despite variations across different time frames, Heilongjiang Province, Jilin Province and Liaoning Province have consistently been identified as the most severely impacted regions regarding cropland non-agriculturalization throughout Northeast China, with proportions exceeding 85%.

Combined with the spatial distribution of non-agricultural cropland in Northeast China from 2000 to 2020 and the crop potential yield data in 2000, the lost GPP caused by non-agricultural cropland was estimated, and the lost GPP in the grids of 30 m × 30 m was obtained, as shown in Fig. 3. From 2000 to 2020, the total amount of lost GPP caused by non-agricultural cropland in Northeast China was 325.20×10^4 tonnes, and its spatial distribution was very similar to that of cropland, mainly concentrated in the central and southern parts of Northeast China, especially in Jilin and Liaoning provinces. There were significant differences in lost GPP among four provinces (regions). The largest lost GPP was in Liaoning Province and Jilin Province, which
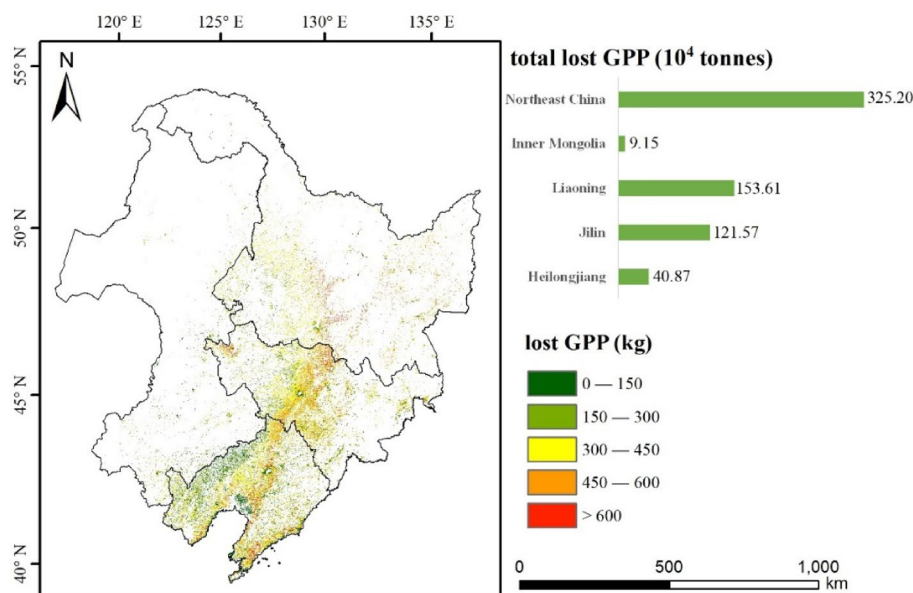
Fig. 3. Loss of GPP due to cropland non-agriculturalization in each 30 m × 30 m grid during 2000–2020[1].
[1]The map was created by ArcGIS 10.8 software (https://desktop.arcgis.com/zh-cn/arcmap/index.html).

were 153.61×10^4 tonnes and 121.57×10^4 tonnes respectively, accounting for about 85% of the total lost GPP in the whole region. In contrast, the lost GPP in Heilongjiang Province and Inner Mongolia caused by non-agricultural cropland was relatively small, and the lost GPP in Inner Mongolia was only 9.15×10^4 tonnes. For each 30 m × 30 m grid loss of GPP, in the relatively flat terrain, the soil was relatively fertile in the middle of Jilin Province and Liaoning Province, up to 450 kg, some regions even more than 600 kg. However, in the southwest of Heilongjiang Province and the west of Liaoning Province with higher altitude, the west of Jilin Province and the Inner Mongolia region where the land desertification was more serious, the lost GPP in the single grid was even less than 300 kg, and in the west of Liaoning Province, most of the lost GPP was less than 150 kg. This is mainly due to the fact that the regions with flat terrain and fertile soil will lead to non-agricultural cropland, and thus lose more GPP.

Impact of non-grainization on GPP
Loss of GPP due to cash crop cultivation
Figure S4 shows the changes of the proportion of grain crop sown area in Northeast China and four provinces (regions) from 2000 to 2020. During this period, the proportion of grain crop sown area in Northeast China basically showed an increasing trend year by year, from 83.14% in 2000 to 91.99% in 2020, but the change trends of the proportion of grain crop sown area in the four provinces (regions) were not the same. For Heilongjiang Province, the change trend was very similar to that of Northeast China, and it was basically in a continuous increasing trend from 86.50 to 97.26% during 2000–2020. For Jilin Province, it was in a fluctuating upward trend from 82.57 to 92.37% during 2000–2020. For Liaoning Province, it showed a relatively significant trend of first decreasing, then increasing, and then maintaining a steady trend. From 2000 to 2003, it continued to decrease from 78.92 to 73.74%, and then increased to 85.18% in 2006. After that, it remained stable at about 82.00% in the next 14 years. For Inner Mongolia, the proportion of grain crop sown area fluctuated sharply from 2000 to 2020, showing a trend of first decreasing, then increasing, then decreasing and then increasing. Overall, the increase was 5.88% over 21 years. Compared with the four provinces (regions), Heilongjiang Province has the largest grain crop sown area in 21 years, followed by Jilin Province, Liaoning province and Inner Mongolia. It could be seen that the whole Northeast China and four provinces (regions) attached great importance to food production since 2000. The proportion of cash crops was gradually shrinking, and the proportion of grain crops was gradually increasing.

Figure S5 shows the impact of cash crop planting on GPP in each region based on the changes of the proportion of grain crop sown area. Due to the increase of grain crop sown area in Northeast China and four provinces (regions) from 2000 to 2020, it had a positive impact on GPP. The increase of grain crop sown area in Northeast China resulted in an increase of 1134.76×10^4 tonnes in GPP. The increase of grain crop sown area in each province led to an increase in GPP, such as 754.73×10^4 tonnes in Heilongjiang Province, 263.55×10^4 tonnes in Jilin Province, 92.92×10^4 tonnes in Inner Mongolia, and 57.28×10^4 tonnes in Liaoning Province.

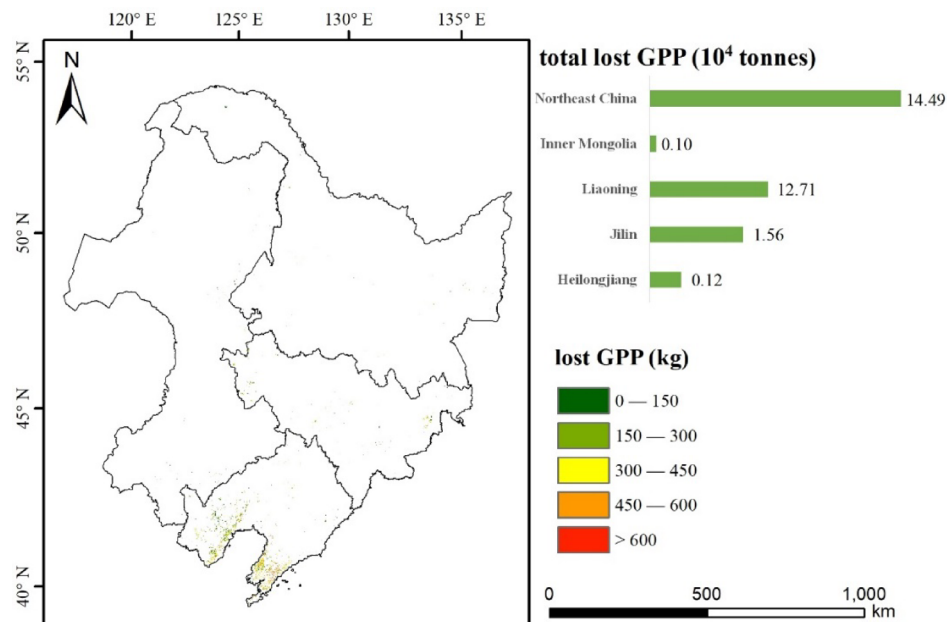*Loss of GPP due to conversion to the orchards*
Figure S6 shows the area and spatial distribution due to the conversion of cropland to the orchards during 2000–2020 and every 5 years (2000–2005, 2005–2010, 2010–2015, 2015–2020). From 2000 to 2020, the area of cropland converted into the orchards in Northeast China was 480.42 km² and the proportion was about 0.13%. The regions where cropland was converted into the orchards were mainly distributed in the southern part of Northeast China, especially in the south of Liaoning Province (Fig. 8). The analysis of different time periods showed that the area of cropland converted into the orchards from 2005 to 2010 was the largest, which was similar to the non-agriculturalization, and was 1,040.68 km² followed by the area of 203.90 km² from 2015 to 2020. From 2010 to 2015, the area of cropland converted into the orchards was the smallest, only 26.87 km².

Combined with the spatial distribution of the conversion of cropland to the orchards in Northeast China from 2000 to 2020 and the crop potential yield data in 2000, this study estimated the lost GPP caused by the conversion of cropland to the orchards, and obtained the lost GPP in each 30 m × 30 m grid, as shown in Fig. 4. From 2000 to 2020, the total lost GPP caused by conversion of cropland to the orchards in Northeast China was 14.49×10^4 tonnes, mainly distributed in the southern part of Liaoning Province. There were significant differences in lost GPP among the four provinces (regions). The largest lost GPP was in Liaoning Province, which was 12.71×10^4 tonnes, accounting for 87.72% of the total lost GPP in the whole region. The lost GPP caused by the conversion of cropland to the orchards in the other three provinces (regions) was relatively small, and the lost GPP in Inner Mongolia was only 0.10×10^4 t. The lost GPP per 30 m × 30 m grid can reach 300 kg in most regions, and even exceed 600 kg in some regions of southern Liaoning Province. This was mainly due to the relatively undulating terrain in the southern part of Liaoning Province, where many sloping cropland were converted into the orchards and more GPP was lost.
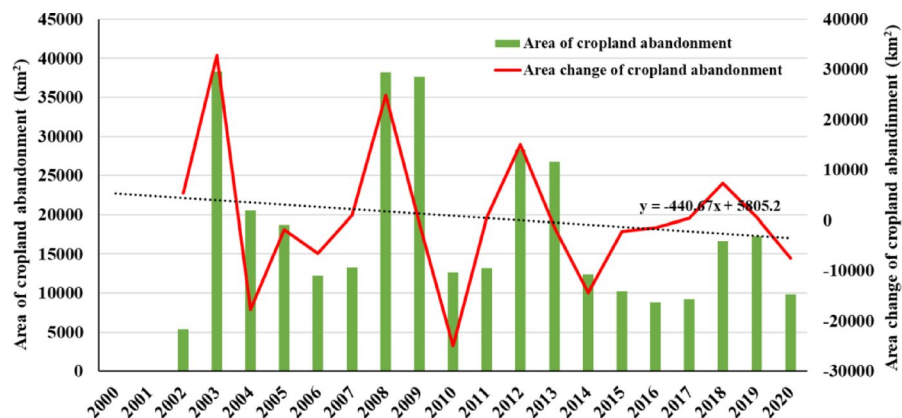
Impact of cropland abandonment on GPP
Overall trend of cropland abandonment
By tracking the change of land cover types in each grid from 2000 to 2020, this study obtained the annual cropland abandonment maps of Northeast China from 2000 to 2020. As cropland abandonment refers to the cropland that has not been cultivated for two years or more, the earliest year that the cropland abandonment map can be obtained was 2002. Figure 5 shows the area of cropland abandonment and the annual changes of cropland abandonment in each year from 2002 to 2020. It can be seen that before 2010, there was a lot of abandoned cropland, among which the area of abandoned farmland in 2003, 2008 and 2009 was the largest, which was 38.24, 38.21 and 37.60 thousand km² respectively. After 2010, the abandoned cropland decreased somewhat, which was less than 15.00 thousand km² in most years. According to the linear trend line of cropland abandonment in Fig. 10 (y=-440.67x+5805.2), the area change of cropland abandonment in Northeast China

Fig. 4. Loss of GPP due to the cropland converting to the orchards in each 30 m × 30 m grid during 2000–2020[1]. [1]The map was created by ArcGIS 10.8 software (https://desktop.arcgis.com/zh-cn/arcmap/index.html).

Fig. 5. Annual area and area change of cropland abandonment during 2000–2020[1]. [1]The map was created by Microsoft Excel 2020 software (https://www.microsoft.com/zh-cn/microsoft-365/excel).

showed a decreasing trend from 2002 to 2020, and in about half of the years decreased compared with the previous year.

Duration of cropland abandonment from 2000 to 2020
In this study, the duration of cropland abandonment in each grid from 2000 to 2020 was analyzed, which were 1–3 years, 4–6 years, 7–9 years and 10–11 years, respectively. Among them, the year in which cropland was abandoned for the most time was 11 years, as shown in Figure S7. It can be seen that no matter in the whole Northeast China or the four provinces (regions), the duration of cropland abandonment in most regions was 1–3 years. Among them, 80.113% of the abandoned cropland in Jilin Province lasted for 1–3 years, and about 78% in other regions. Secondly, the area of abandoned cropland with a duration of 4–6 years in the whole Northeast China and various provinces (regions) accounts for about 20%. The area of abandoned cropland with a duration of more than 7 years was very small, less than 1%, and that with a duration of more than 10 years was less than 0.01%, which cannot be shown in the following bar chart.

Spatio-temporal distribution of cropland abandonment
We added the spatial distribution maps of abandoned cropland in each year, identified the grids of abandoned cropland in each year, and abtained the spatial distribution maps of abandoned cropland in each 30 m × 30 m grid in three periods (2002–2010, 2010–2020, 2002–2020) (Figure S8). It can be seen that the abandoned
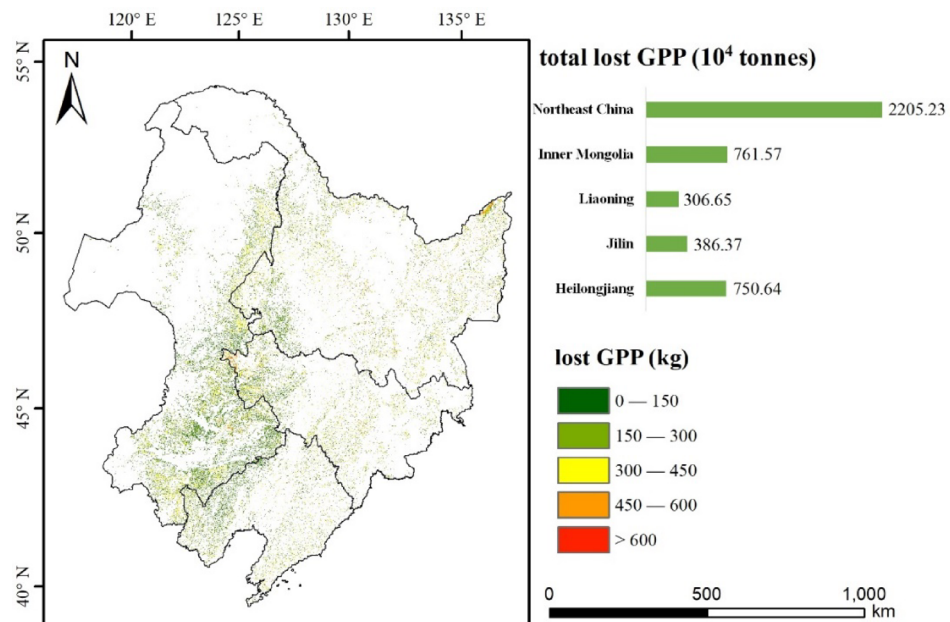
Fig. 6. Loss of GPP due to cropland abandonment in each 30 m × 30 m grid during 2000–2020[1]. [1]The map was created by ArcGIS 10.8 software (https://desktop.arcgis.com/zh-cn/arcmap/index.html).

cropland in the three periods was widely distributed in the western part of Northeast China, especially in Inner Mongolia. From 2002 to 2020, the total area of abandoned cropland was 143.30 thousand km² while the total area of abandoned cropland before and after 2010 was 101.40 thousand km² and 75.18 thousand km²respectively.

Impact of cropland abandonment on GPP
The cropland abandonment will directly lead to the decline of grain sown area and total grain production. Based on the identification results of abandoned cropland, combined with the crop potential yield data in 2000, the lost GPP caused by abandoned cropland during 2000–2020 was estimated (Fig. 6). The total lost GPP in Northeast China from 2000 to 2020 was $2,205.23 \times 10^4$ tonnes. Compared with the four provinces (regions), cropland abandonment mainly occurred in Inner Mongolia, so the lost GPP of cropland abandonment in Inner Mongolia was also the largest among the four provinces (regions), which was 761.57×10^4 tonnes, followed by Heilongjiang Province, which lost 750.64×10^4 tonnes of cropland abandonment. The lost GPP due to cropland abandonment in Liaoning Province and Jilin Province was 306.65 and 386.37×10^4 tonnes, respectively.

Discussion
Cropland use changes affecting GPP in Northeast China
Our study showed that since 2000, the cropland non-agriculturalization caused by the urbanization of Northeast China, the cropland non-grainization including the planting of cash crops and the conversion of cropland to orchards, and the cropland abandonment have posed a serious threat to grain production. We aggregated the impact of three aspects of cropland use changes on GPP as shown in Figure S9. For the entile Northeast China, the three types of cropland use changes caused a total loss of $1,410.16 \times 10^4$ tonnes of GPP. The loss of GPP in the four provinces (regions) from more to less was 713.54×10^4 tonnes in Inner Mongolia, 415.69×10^4 tonnes in Liaoning Province, 245.95×10^4 tonnes in Jilin Province and 36.90×10^4 tonnes in Heilongjiang Province.

The main cropland use change causing the loss of GPP in Heilongjiang Province and Inner Mongolia was cropland abandonment (750.64×10^4 and 761.57×10^4 tonnes respectively), but the phenomenon of non-agriculturalization and the conversion of cropland to orchards in the two regions was not obvious. In the study of Li et al.[19]Heilongjiang Province and Inner Mongolia had a large scale of cropland abandonment, which was 62.19×10^4 and 78.85×10^4 ha respectively in 2017. The conclusions of the two studies were quite consistent. This was mainly because in Heilongjiang Province and Inner Mongolia, the agricultural supporting facilities and agricultural socialization service system were relatively weak. The gradual deterioration of agricultural production conditions seriously reduced the enthusiasm and participation of farmers in grain planting, and then led to the abandonment. At the same time, the increase of non-farm profit opportunities and the decline of agricultural comparative returns lead to changes in the allocation behavior of agricultural labor factors. Under the dual effects of labor loss and aging, the abandoned cropland showed a large scale and agglomeration distribution characteristics.

For Jilin and Liaoning provinces, in addition to the large area of abandoned cropland, the loss of GPP caused by cropland non-agriculturalization was also large (121.57×10^4 and 153.61×10^4 tonnes respectively). The Lower Liaohe Plain area was the largest "granary" in Liaoning Province, and the urbanization development intensified the phenomenon of cropland non-agriculturalization, with the area reaching 2201.52 km² from 2000 to 2020[35].

The main reason was that the terrain of the Lower Liaohe Plain was generally flat, with more rivers, developed transportation and rich mineral resources. Meanwhile, in recent years, rural population has shifted to urban regions in large numbers. Favorable natural conditions and the rapid expansion of urban population made the urbanization process accelerate rapidly, occupying a large amount of cropland around cities and towns, resulting in large loss of GPP. In recent years, the process of cropland non-agriculturalization in Jilin Province has been gradually accelerated, which was mainly affected by the comprehensive effects of economic development, social development and policy mechanism[36]. In addition, although the conversion of cropland to orchards was not obvious in Northeast China, compared with the other provinces (regions), the phenomenon was very common in Liaoning Province, especially in the southern region, resulting in the lost GPP of 12.71×10^4 tonnes. The main reason was that the terrain in the southern region of Liaoning Province was highly undulating, and the slope land was suitable for the growth of fruits such as apples and cherries, and it can obtain higher economic benefits than grain crops.

Since 2000, the proportion of cash crops in cropland in Northeast China has decreased year by year, which led to an increase in GPP, especially in Heilongjiang Province. The main reasons include three aspects. Firstly, the Heilongjiang government has implemented a series of policies to support grain production, including subsidies, loans and technical services, to encourage farmers to increase the grain planting area. Secondly, Heilongjiang Province, as a major commodity grain production base, needs to increase grain planting to meet the national grain demand. Finally, the promotion of modern agricultural techniques in Heilongjiang Province, such as high-yielding seeds, mechanized farming, and precision agriculture, has also improved the efficiency of grain production.

Suggestions for cropland protection

Under the severe situation of cropland use changes in Northeast China, such as non-agriculturalization, non-grainization and abandonment, and the serious impacts on GPP, this study puts forward the following suggestions for cropland protection.

First of all, the essence of cropland non-agriculturalization is the process of transforming cropland into built-up land, so this part of cropland is generally irreversible and difficult to reclaim, which in turn causes permanent loss of GPP[37]. Since non-agriculturalization has seriously threatened national and regional food security and sustainable cropland use, China has successively issued a series of management policies to curb non-agriculturalization. In 2020, The General Office of the State Council officially issued the Notice on Resolutely Stopping the "Non-agricultural" Cultivation. In 2022, the No.1 central document once again proposed to implement hard measures for farmland protection to ensure national food security. In some regions of Jilin Province and Liaoning Province, where cropland non-agriculturalization is more serious, it is necessary to resolutely curb urban sprawl in the future. Measures such as improving the intensive utilization rate of urban and rural land, ensuring the financial needs of local governments, perfecting the responsibility assessment mechanism of cropland protection targets, perfecting the balance system of cropland occupation and compensation, perfecting the land circulation mechanism, and promoting the development of agricultural science and technology can be taken to prevent the further intensification of cropland non-agriculturalization[36].

For Northeast China, the phenomenon of cropland non-grainization is not obvious. In 2020, the proportion of non-grainization in Northeast China was only 7%, far less than 46% in southwest China and 41% in South China[18]and has been decreasing year by year during 2000–2020. The increase in sown area of grain crops has led to an increase in GPP, which has played a positive role in ensuring food security.

As one of the important forms of cropland resource change, cropland abandonment not only directly leads to the decrease of grain sown area, but also causes soil erosion and land degradation, which in turn leads to the decrease of grain production environment and cropland production capacity[38]. Cropland abandonment is very serious in four provinces (regions) in Northeast China, mainly in Heilongjiang Province and Inner Mongolia. Although cropland divination balance has been implemented in some regions, the quality of additional cropland is often poor and gradually abandoned[33]. However, since cropland abandonment can be restored, agricultural production should be resumed as soon as possible. In the meantime, we should follow the trend of urban-rural integration and agricultural and rural development, strengthen the input of modern factors of agricultural production and policy support in the main grain producing areas, and build the elastic mechanism of grain production-cultivated land fallow space conversion to ensure the food security.

Limitations and uncertainties in this study

This study had some limitations and uncertainties. First, this study aimed to comprehensively explore the impacts of different types of cropland use changes on GPP in Northeast China, considering the impacts of three aspects of cropland non-agriculturalization, non-grainization and abandonment, but didn't consider the impacts of agricultural production input changes in cropland, such as mechanization level, fertilizer and pesticide application, on GPP. In fact, this is also an important aspect of cropland use change. Future study should explore more precise methods to accurately assess its impact on grain production.

Secondly, for the identification of cropland abandonment, this study adopted the definition of abandoned cropland given by the 2011 International Symposium on Land Consolidation and Land Reserve, which is that cropland that has not been cultivated for more than two consecutive years. Therefore, this study used the GLC-FCS30 land cover datasets as the data source to obtain the spatial distribution of abandoned cropland in each year from 2002 to 2020. There were many studies on the identification of abandoned cropland according to this method[19,39]. However, in 1995, Food and Agriculture Organization (FAO) of the United Nations defined abandoned farmland as farmland that has not been used for agricultural production or other agricultural purposes for at least five years. Referring to this definition may lead to excessive number of abandoned cropland

currently identified. It can be seen that scholars have different opinions on whether the idle cropland is the length of time of abandoned cropland, which may then lead to differences in the identification results.

Conclusion

Based on the actual problems of cropland use in Northeast China since 2000, this study quantitatively analyzed the impacts of three main aspects of cropland use changes (non-agriculturalization, non-grainization and abandonment) on GPP at the grid scale. From 2000 to 2020, the cropland area of the entire Northeast China increased by about 2.10% (9,275.51 km^2). The cropland area decreased slightly (1,274.61 km^2) from 2000 to 2008, and continued to increase (10,550.23 km^2) from 2008 to 2020. Since 2000, due to climate warming, cropland suitable for planting areas expanded to the north, and the urbanization process of cropland occupied in the south accelerated, the gravity center of cropland moved to the northeast with a moving distance of 9.18 km.

The total loss of GPP in Northeast China was 1,410.16×10^4 tonnes due to the non-agriculturalization, non-grainization and abandonment of cropland, among which cropland abandonment was the main type of cropland use change leading to the loss of GPP. The dominant type of cropland use change was different in different provinces (regions), which led to different degrees of GPP loss. Heilongjiang Province and Inner Mongolia were dominated by cropland abandonment, resulting in the loss of GPP of 750.64×10^4 and 761.57×10^4 tonnes respectively. Jilin Province and Liaoning province were mainly non-agriculturalization, resulting in the loss of GPP of 121.57×10^4 and 153.61×10^4 tonnes respectively. At the same time, the conversion of cropland to orchards was more common in southern Liaoning Province. Since 2000, the proportion of sown area for grain crops in Northeast China and other provinces (regions) has increased year by year, resulting in an increase of 1,134.76×10^4 tonnes in GPP, which has made up for the loss of GPP caused by other cropland use changes to a certain extent.

For Heilongjiang Province and Inner Mongolia, where cropland abandonment was relatively serious, this study puts forward the suggestions of restoring agricultural production on abandoned cropland as soon as possible, strengthening the input and policy support of modern agricultural production factors in main grain producing areas, and constructing the elastic mechanism of grain production-farmland fallow conversion. In order to prevent the intensification of cropland conversion, some measures should be taken in Jilin and Liaoning provinces, such as improving the intensive utilization rate of urban and rural land, ensuring the financial needs of local governments, perfecting the responsibility assessment mechanism of cultivated land protection targets, perfecting the balance system of cultivated land occupation and compensation, and perfecting the land circulation mechanism.

Data availability

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Author contributions

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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