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Unveiling Grain Production Patterns in China (2005-2020) towards Targeted Sustainable Intensification

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Abstract:

CONTEXT

Long-term historical information on national-scale grain production is critical for ensuring food security but often limited by the lack of geospatial data.

OBJECTIVE

This study aims to conduct the first systematic investigation of grain Cropping Patterns (CP) in China over the past two decades, shedding light on the roles of grain expansion and intensification in sustainable agriculture.

METHODS

This study proposes a framework to fully characterize grain production patterns considering crop types, cropping intensity and patterns based on spatiotemporal continuous ChinaCP datasets (2005-2020). Four indicators were developed for measuring the Reality to Capability Ratio (RCR) of grain production regarding the total yield and sow area, the cropland extent and cropping intensity. The capability of grain production was derived based on grain cultivation history.

ESULTS AND CONCLUSION

There was a huge gap between the reality and capability of grain production in China, which varied with grain crop types and cropping patterns. At national level, a vast majority (96%) of cropland was capable of grain production, and two fifths of cropland quantified for double grain cropping. However, only 46.65% and 24.89% of the capability was implemented for grain or double-grain cropping in 2020. Maize, rice, and wheat was ever cultivated in 76.88%, 57.05%, and 25.18% of national cropland, respectively. Winter wheat plays an important role in stabilizing grain production by double grain cropping, accounting for 7/8 continuously grain-cultivated areas. However, the RCR of double rice was only 7% in 2020. Bridging these gaps could potentially triple grain production, however, achieving this increase poses challenges due to a series of constraints related to cropland fraction, topographic conditions and lack of agricultural labors along with rapid urbanization. This study found that there was a continuous Northeastward movement & countryside shift in grain production. Continuous support for long-term active agricultural systems is crucial to ensure sustainable grain production in China, with a special emphasis on key grain productive regions, considering targeted cropping patterns and regional disparities.

SIGNIFICANCE

This study enhances our understanding of grain production systems in China based on long-term cultivation histories. Findings can inform the development of more geographic-targeted policies concerning grain cropping intensifications to ensure food security and environmental sustainability in developing countries.

Keywords: Non-grain production; Grain security; Cropping patterns; Spatiotemporal process; China.

1. Introduction

The reduction of hunger and improvement of food security have become key priorities in the Sustainable Development Goals (SDGs) for the 2030 agenda (Urfels et al., 2023; Yang et al., 2020). Global food security is facing continuous threats due to increasing climate changes, rising food demand, and uncertainties like armed conflicts (Bentley et al., 2022; Renard and Tilman, 2019). The repercussions of high food prices and food insufficiency have led to severe social and political disturbances in several countries (Ghose, 2014). Particularly, food security remains a critical challenge, especially in smallholder agricultural systems (Cui et al., 2018). To address these issues, it is crucial to promote stabilizing grain production and ensuring self-sufficiency (Bentley et al., 2022; Olsen et al., 2021). However, concerns are arising about the sustainability of future grain production (Yuan et al., 2021). Firstly, the rapid expansion of Non-Grain Production (NGP) on cropland is increasingly threatening food security, and this phenomenon is common across the globe (Liang et al., 2023). Secondly, major grain production regions, including China, have experienced a slowdown or even reached a plateau in yield rates (Grassini et al., 2013). Thirdly, grain production has negative environmental impacts, including the consumption of natural resources and greenhouse gas emissions (Jain et al., 2023; Potapov et al., 2022).

Increasing concerns about the issues mentioned above underscore the critical importance of sustainable intensification of existing cropland (Cassman and Grassini, 2020; Shen et al., 2023; Zuo et al., 2018). Over the past few decades, the demand for agricultural production has often been met through cropland expansion and agricultural intensification (Fróna et al., 2019). However, cropland expansion has led to the replacement of natural vegetation, including protected forests, primarily responsible for increased food production in Southeast Asia, Africa, and South America (Potapov et al., 2022; Zeng et al., 2018). On the other hand, agricultural intensification has enabled higher food production within existing cropland by increasing crop yields and cropping intensity (Wu et al., 2018). As we strive to ensure food security, our food production systems must also consider the environmental needs of future generations (Alemu, 2022; Ambikapathi et al., 2022). Changes in the extent and intensity of cropland have significant implications for human well-being (Finch, 2020; Li et al., 2023). Particularly, increased grain production plays a crucial role in reducing hunger and poverty in smallholder agricultural systems, which constitute 84% of global farms (Jain et al., 2023). To support smallholder agriculture, promoting domestic food production becomes even more vital, as these systems face numerous challenges stemming from limited access to information and technologies (Harvey et al., 2018). To achieve more refined farming management plans, it is essential to advocate for specific policies targeted towards cropland management (Liang et al., 2023; Upcott et al., 2023). The implementation of site-specific sustainable intensification requires thorough investigations of historical grain production based on cropping types and patterns (Mahlayeye et al., 2022; Rudel et al., 2009; Smith et al., 2023). Such detailed analysis will contribute to a more informed approach towards sustainable agricultural practices and help address the complexities of food security and environmental preservation (Li et al., 2023).

China possesses the largest smallholder farms, responsible for producing 80% of the nation's food (Lowder et al., 2021). Given its significant population, grain production and food sufficiency in China have been, and will continue to be, crucial in ensuring global food security (Cui and Shoemaker, 2018). China faced substantial food shortages in the mid-20th century but has made remarkable progress in grain productivity since the land contract reform in the 1980s (Fróna et al., 2019). In the early 21st century, the Chinese government implemented a series of robust policy measures to achieve grain self-sufficiency (Huang and Yang, 2017). Over the past six decades, annual grain production in China has increased fivefold, and the country has achieved self-sufficiency in grain since the late 20th century (Li et al., 2014). The agricultural systems in China have achieved significant milestones but have also undergone substantial changes in terms of cropping intensity and crop types (Qiu et al., 2017a). Accurate observations and understanding the spatial-temporal process of grain production is essential to address the growing global food insecurity (Ayanlade and Radeny, 2020; Laborte et al., 2017). To guide sustainable agricultural intensification, it is crucial to quantify the grain production capability on every hectare of cropland (Van Ittersum et al., 2013). However, a thorough understanding of grain production history based on crop types and cropping patterns is currently lacking (Upcott et al., 2023; Zhu et al., 2022). There is an urgent need for systematic investigations into the grain cropping history using annual cropping patterns datasets across conterminous China in order to fill these knowledge gaps.

This study aims to address these requirements based on spatiotemporal explicit annual datasets of cropping patterns during the past two decades. The China Cropping Pattern Maps (ChinaCP) provided detailed information on staple grain cropping patterns in recent years (since 2015) (Qiu et al., 2022a), and this study further developed the annual continuous ChinaCP datasets since 2005. Continuous crop maps for multiple years provide critical time-series data on the temporal and spatial patterns of food production and shortages (Massey et al., 2017). The recently published ChinaCP dataset allows for tracking the spatiotemporal history of grain cultivation extent and intensity and their possible drivers associated with biophysical or socioeconomic conditions (Qiu et al., 2022a). However, the ChinaCP dataset has not been fully investigated yet, with a particular oversight in understanding the evolution of grain cropping patterns (Jin and Zhong, 2022). This study comprehensively investigates the grain cultivation history and the gaps between current grain production and its capability, based on spatiotemporal continuous datasets covering conterminous China over the past two decades. Specifically, we directly address the following scientific questions: (1) How can we depict the grain cultivation history using the parameters of extent, intensity, and frequency of grain crops? (2) What is the potential capacity of grain production concerning cropped areas and cropping intensity? (3) Are there significant disparities between actual grain production and its capacity, and if so, where do these gaps exist, and how are these gaps associated with extent and intensity?

2. Study area and methodology

2.1. Study area

China ranked first in global cereal production (FAO, 2019). Specifically, China ranked first in rice and wheat production, and second in maize production (after the United States) in the world (Halweil, 2021). The cultivation history of these three major cereals, paddy rice, wheat, and maize, spans a long period in China. Together, these three staple crops accounted for 97% of the national cereal areas in 2020 (Qiu et al., 2022a). China is divided into nine agricultural regions (1985): Northeast China (A), Huang-Huai-Hai Plain (North China Plain, B), Middle and lower reaches of the Yangtze River Plain (C), South China (D), Southwest China (E), Qinghai-Tibet (F), Gan-Xin (G), Loess Plateau (H), and Inner Mongolia and along the Great Wall (I). Paddy rice is predominantly cultivated in Northeast China and the Middle-lower Yangtze River plain (Zhang et al., 2015). Over the past two decades, the rice cropping systems in China have undergone significant changes. Rice-sown areas decreased in southern China but expanded in Northeast China (Xin et al., 2020). In particular, the cultivation of double rice was dominant in southern China in the early 2000s but rapidly declined in the 2010s (Lai et al., 2020). Maize has surpassed paddy rice to become the top grain crop in China, with a wide distribution across the entire country (Qiu et al., 2018). Maize is cultivated as spring maize (single maize) or summer maize, and summer maize is commonly double-cropped with winter crops such as winter wheat. Nearly all of the wheat production in China comes from winter wheat, which is commonly cultivated through double cropping in the North China Plain (Li et al., 2019).

2.2. **Datasets**

2.2.1. Multiple spectral indices time series datasets based on MODIS images

The 500 m 8-day composite Moderate Resolution Imaging Spectroradiometer (MODIS) surface reflectance product, MOD09A1, was chosen for its long-term observations and high-frequency revisit capability (Han et al., 2022). Three spectral indices were calculated: the 2-band Enhanced Vegetation Index (EVI2), the Land Surface Water Index (LSWI), and the Normalized Multi-band Drought Index (NMDI). EVI2 was derived using surface reflectance values from the red and near-infrared red bands (Jiang et al., 2008). LSWI was computed using surface reflectance data from the near-infrared red and short-wave infrared bands (Xiao et al., 2005). NMDI was obtained based on the near-infrared band and two short-wave infrared bands (Wangle and Qu, 2007).

$$\mathrm{EVI2} = 2.5 \times \left(\rho_{NIR} - \rho_{\mathrm{Red}}\right) / \left(\rho_{NIR} + 2.4 \times \rho_{\mathrm{Red}} + 1\right) \qquad (1)$$

$$\mathrm{LSWI} = \left(\rho_{NIR} - \rho_{SWIR6}\right) / \left(\rho_{NIR} + \rho_{SWIR6}\right) \qquad (2)$$

$$NMDI = \frac{\rho_{NIR} - \left(\rho_{SWIR6} - \rho_{SWIR7}\right)}{\rho_{NIR} + \left(\rho_{SWIR6} - \rho_{SWIR7}\right)} \quad (3)$$

Where ρ_{NIR} , $\rho_{\mathrm{Re}d}$, ρ_{SWIR6} and ρ_{SWIR7} represented the surface reflectance values from the Near-infrared, red, short wave infrared band centered at 1640 nm (1628 - 1652 nm) and 2130 nm (2105 - 2155 nm), respectively.

A daily continuous time series dataset was created for each spectral index (EVI2, LSWI, and NMDI) for the years 2005-2020. Cloud-free observations were used for the development of these datasets, employing the Whittaker Smoother (WS) technique (Eilers, 2003). The WS smoother has shown to effectively characterize crop growth cycles, making it a suitable choice for this study (Qiu et al., 2016a).

2.2.2. Maps of cropping patterns with descriptions of grain crops in China from 2005 to 2020

CPChina datasets provided information on cropping intensity with detailed information on grain crop types. Specifically, the cropping patterns included single cropping of three staple grain crops (rice/maize/wheat) and other crops, multiple cropping of staple grain crops (i.e. rice-maize), multiple cropping of staple grain crops (rice/maize/wheat) plus other crops (rotation of grain crop plus others), and others. The primary double cropping patterns of grain production, such as winter wheat-maize, winter wheat-rice, and double rice, can be effectively tracked using the spatiotemporal continuous CPChina datasets. The long-term spatiotemporal continuous CPChina datasets were developed based on MODIS time series images during 2005-2020 (Qiu et al., 2022a). The CPChina datasets has been exploited for a series of applications such as improving the predictability of cropland quality and the impacts of natural disaster through incorporating cropping patterns (Liu et al., 2023; Sun et al., 2023).

The CPChina datasets were generated using a series of robust mapping algorithms for deriving cropping intensity and three staple grain crops (rice, maize, and wheat) proposed in recent references (Qiu et al., 2022a; Qiu et al., 2016b). Knowledge-based approaches, which refer to phenological features, have demonstrated good performance in spatiotemporal generalization while requiring less costly and time-consuming reference data collection (Adamo et al., 2020; Tian et al., 2022). Cropping intensity was determined based on three key features: the skeleton width, the maximum number of strong brightness centers, and the intersection of their scale intervals, obtained from the wavelet spectra transformed from the Vegetation Indices (VI) temporal profiles (Qiu et al., 2016b). These three staple crops were identified by several novel and robust phenological indicators by exploring their unique characteristics based on vegetation and water indices time series. Specifically, paddy rice is distinguished by its lower values in the ratio of change amplitude in Land Surface Water Index (LSWI) to VI from tillering to heading dates (Qiu et al., 2015). Maize could be mapped based on the larger values in the ratio of cumulative positive slope to the negative slope of NMDI, as it exhibits consistently high leaf moisture during the heading stage (Qiu et al., 2018). Winter wheat can be extracted based on its larger values in VI variations during the estimated vegetative and reproductive stages (Qiu et al., 2017b). These above mapping algorithms achieved good performances in large-scale applications, which were applied at a national scale in China with no requirements for regional or yearly adjustments (Qiu et al., 2018; Qiu et al., 2015; Qiu et al., 2017a; Qiu et al., 2017b).

2.2.3. Cropland distribution data and other datasets

The 30 m GlobeLand30 data was utilized to derive the distribution data of croplands (Chen et al., 2014). This dataset was selected due to its relatively high accuracy (overall accuracy=85.72% in 2020) and easy accessibility (www.globallandcover.com). To match the resolution of the MODIS images, the 30 m cropland pixels with references to the GlobeLand30 data were aggregated to form a 500 m cropland map. Other datasets used in this study included socio-economic data and crop calendar data. Socio-economic data were obtained from the National Statistical Bureau of China (NSBC) (http://www.stats.gov.cn/english/). The crop calendar data recorded the dates of key phenological stages for the three staple crops. Additionally, the topography map (Cheng et al., 2011) was employed to investigate the influences of landform types on the NGP process.

2.3. Methodology

Grain production system changes across space and time. The spatiotemporal patterns of grain production were systematically revealed through estimating the capability based on historical ChinaCP datasets, exploring the gaps between capability and reality and their drivers (Figure 1). First, this study investigated the spatiotemporal process of grain production by cropping patterns. The frequency of cultivated grain crops was calculated for total grain production and different grain cropping patterns. Second, the capability of grain production was estimated based on cultivation history. Third, the gaps between reality and capability of grain cultivation were explored with a full consideration of grain crop type, cropped extent and cropping intensity. Finally, the influencing factors of grain production were explored and the spatiotemporal variability of NGP processes shaped by these drivers was presented. Several indicators were proposed for these above purposes. These calculations were performed using a per-pixel strategy and aggregated at municipal, provincial, and national levels. Detailed descriptions were provided as follows.

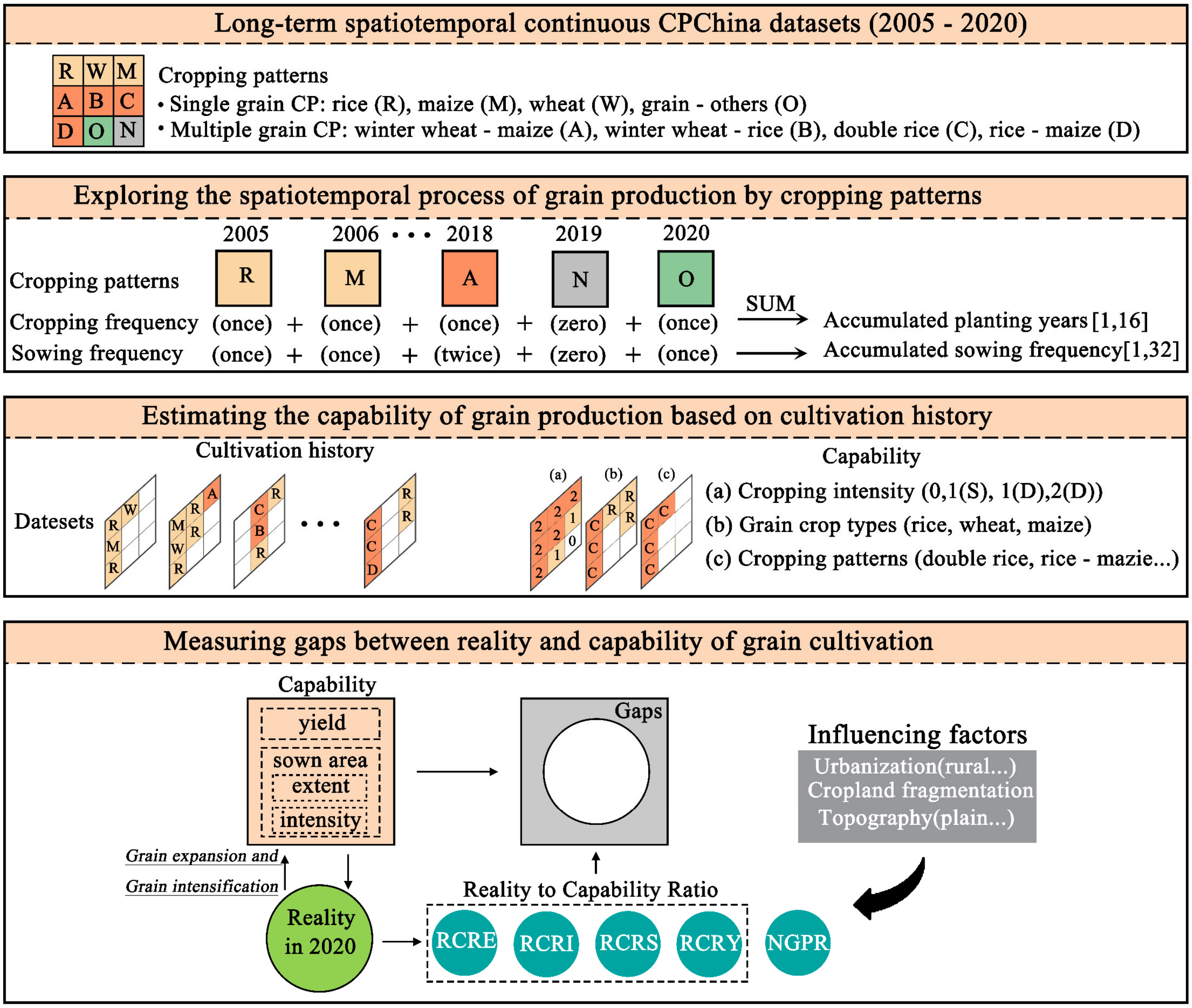


Figure 1. The framework for unveiling grain production patterns

2.3.1. Exploring the spatiotemporal process of grain production by cropping patterns

This study aimed to investigate the spatiotemporal processes of grain production, considering grain crop types, cropping intensity, and cropping patterns during the study period (2005-2020). Two indicators, namely the Accumulated Planting years (APY) and the Accumulated Sowing Frequency (ASF), were proposed to measure the frequency of cultivated grain crops. For one specific year, if a pixel was cultivated by single maize, the APY and ASF of grain production would be increased by 1; if a pixel was cultivated by double rice, the APY and ASF of grain production would be increased by 1 and 2, respectively. Large values in APY and ASF revealed higher frequency of grain production. Specifically, the APY indicator ranged from 0 to 16, where a value of 16 suggested that the pixel was continuously cultivated with grain crops during the study period (2015-2020). The ASF ranged from 0 to 32, as a pixel with grain production might be cultivated by grain crops once or twice for one specific year (triple grain crops were seldom implemented and not reported in the ChinaCP data in China). A value of zero in APY or ASF represented that the pixel was not been cropped any of three staple grain crops during the study period. These two indicators (APY, ASF) were first estimated for the total grain production, and then for these three staple crops and their cropping patterns. For example, if a pixel was cropped by double rice for one specific year, the APY would be enhanced by 1 for the total grain production and also for cropping pattern of double rice. This study investigated the histograms of APY for total grain production and examined their contributions from different grain cropping patterns (Figure 2). The gravity center of grain production in China was calculated to track its trajectory during the past few decades.

2.3.2. Estimating the capability of grain production based on cultivation history

The capability of grain production was estimated to improve our knowledge of the cropland extent and sown areas suitable for grain production. Cropland's capability of grain production could generally be estimated based on the soil, climatic and topographic conditions (Zhang et al., 2017). Cropland is suitable for single or multiple cropping and could generally be derived regarding biophysical conditions such as the FAO/IIASA Agro-ecological Zones (AEZ) model (Fischer et al., 2002). However, there might be some local constraining factors that were not reflected in existing geospatial datasets. Additionally, the suitability of grain crop rotations was not fully depicted in existing literature and datasets. For example, to what extent and where the grain cropping patterns of winter wheat rotated with rice or maize are capable of production in China? This study estimated the capability of grain production in China based on historical crop maps during the study period. The cropland map capable of grain production was derived based on the ever-cropped area of grain crops based on cropping patterns datasets during 2005-2020. Specifically, if a pixel was ever cropped with any one of these three staple grain crops, it was regarded as capable of grain cultivation. Similarly, a pixel was considered to be capable of multiple-grain cropping only if it was ever implemented during the study period. For example, the cropping pattern of winter wheat plus non-grain crops (i.e. peanut) was regarded as single-grain cropping. This study quantified the grain cropping capability based on the Capability to total Cropland Ratio (CCR) and further evaluated by grain types, cropping intensity, and cropping patterns.

2.3.3. Assessing the gaps between reality and capability of grain production based on extent and intensity

There are two commonly applied NGP indicators: one is the Grain to Crop Ratio (GCR), which is calculated based on the sown area (Lai et al., 2020); another is the NGP Rate (NGPR), which is computed as the ratio of land uncultivated by grain crops to the total cropland (Zhu et al., 2022). Only the first NGP indicator (GCR) could be estimated using the agricultural census data. The GCR might overestimate the NGP since it includes multiple-cropped non-grain crops rotated with grain crops. For example, the GCR would decrease if single cropping of grain was intensified by double cropping with a rotation of non-grain crops. On the other hand, the latter NGP indicator (NGPR) is not sensitive to changes in cropping intensity associated with non-grain crops. However, NGPR cannot reveal the changes in cropping intensity of grain crops, such as the loss of grain production due to changes from double rice to single rice.

The NGP process can be assessed by examining the grain production gaps between actual and potential yields. The estimation of potential yields for grain crops involved utilizing maps of grain production capability, incorporating information on grain crop types, and cropping intensity. Each pixel's potential yield was determined based on the cropping pattern with the highest yield per unit. For example, if a pixel was designated for single cropping of rice, maize, or wheat, the grain crop with the maximum yield per unit was selected. The average yield per unit in 2020 was considered for each grain crops: rice (704 Mt/km^2), maize (632 Mt/km^2), and wheat (574 Mt/km^2). Similarly, if a pixel represented four groups of double-grain cropping, the cropping pattern with the maximum yield per unit was utilized.

These gaps in grain production can further be attributed to the gaps in cropping extent and cropping intensity for grain cultivation. Specifically, the gaps in cropping extent reveal the areas suitable for grain expansion that were left uncultivated in a specific year. On the other hand, the gaps in cropping intensity indicate areas suitable for grain intensification that were not utilized in a specific year. In addition to the commonly used NGP indicators, the NGP process was further investigated using the Reality to Capability Ratio (RCR) concerning cultivation and yield. Instead of relying on the total sown area of crops or cropland in a given year, the capability of grain production was considered. Four indicators were proposed to measure the RCR from different perspectives: the RCR of total grain yield (RCRY), the RCR of sown area (RCRS), the RCR of cropland extent (RCRE), and the RCR of intensification through double grain cropping (RCRI). These indicators were calculated using equations 1-4.

$$RCRY = \frac{Y_{Act}^{t}}{Y_{Cap}} \times 100\% \qquad (1)$$

$$RCRS = \frac{S_{Act}^{t}}{S_{Cap}} \times 100\% \qquad (2)$$

$$RCRE = \frac{E_{Act}^{t}}{E_{Sui}} \times 100\% \qquad (3)$$

$$RCRI = \frac{I_{Act}^{t}}{I_{Cap}} \times 100\% \qquad (4)$$

where Y_{Act}^{t}, S_{Act}^{t}, E_{Act}^{t} and I_{Act}^{t} represented the total grain yield, grain sown area, cropland extent, and cropping intensity of cultivated grain crops in year t, respectively; Y_{Cap}, S_{Cap}, E_{Cap} and I_{Cap} denoted the capability of grain production regarding the total yield, the total sown area, cropland extent, and cropping intensity, respectively. Higher levels of NGP could be revealed by lower values of these three indicators (RCRS, RCRE, RCRI), which measured the grain production gaps from the total sown area, cropping extent and intensity of grain crops, respectively.

2.3.4. Exploring the influencing factors of spatiotemporal processes of grain production

In this study, we conducted a comprehensive examination of the spatiotemporal processes affecting grain production, considering the following influential factors. We addressed cropland fragmentation by utilizing the cropland fraction obtained from the 30 m cropland distribution data (Chen et al., 2015), which we aggregated at a 500 m resolution.

We considered the influence of topographic conditions, which included analyzing the landform types and elevation. For the datasets related to landforms, we sourced them from the Resource and Environment Science and Datacenter (https://www.resdc.cn/Default.aspx). We investigated a series of socio-economic factors such as the urbanization, agricultural machinery, the ratio of irrigation in cropland. We took into account urbanization and measured it based on the distance to the nearest cities at the municipal level or above.

3. Results

3.1 Spatiotemporal process of grain production in China

China has achieved significant milestones in grain production over the past five decades (Figure S1). Grain production doubled despite of an overall decline of GCR since 1978. Specifically, the GCR reached its lowest point (65%) in 2003, slightly improved until 2015-2016, and then declined rapidly during the late 2010s. Grain production in China was primarily achieved by the cultivation of three staple grain crops: rice, wheat, and maize. Notably, the three staple grain crops have consistently contributed more than 80% of the national grain production in China according to agricultural census data (Figure 2). Their significance has grown since 1978, accounting for 91% of national grain production in 2020 (Figure 2). Therefore, these three staple grain crops were considered for exploring the grain cultivation history based on spatiotemporal continuous datasets of cropping patterns from 2005 to 2020.

The analysis of the grain-cropped areas revealed an uneven distribution among different APY categories (Figure 2). There was an overall decline in the extent of grain-cropped fields with the increase of cropping frequency. The cropped fields followed a decay pattern with an exponential function as the APY increased from 1 to 15 ($Y=301413*e^{-0.118x}$, $R^2=0.9848$). There were around two-thirds of Ever Grain Cropped fields (EGC, 2.18 million km^2) cultivated with grain crops for less than 8 years. Specifically, 34.80% of EGC were cultivated by grain crops for no more than 3 years. In contrast, there were only 8.45% of EGC was frequently cultivated (APY=13-15). It is essential to highlight that there were 149,447 km^2 areas (6.92% of EGC, 6.63% of cropland) continuously cultivated with grain crops during 2005-2020. These Continuously Grain-Cropped lands (CGC, APY=16) were predominantly found in the North China Plain (Figure 2), which was mainly attributed by winter wheat (87.14% of CGC). The winter wheat uniquely displayed a continuous increase with the cropping frequency (APY) by double cropping patterns. Less frequently cultivated croplands were primarily used for single cropping of maize or paddy rice. Lessons from grain cultivation history indicated that double cropping of winter wheat played a significant role in stabilizing grain production.

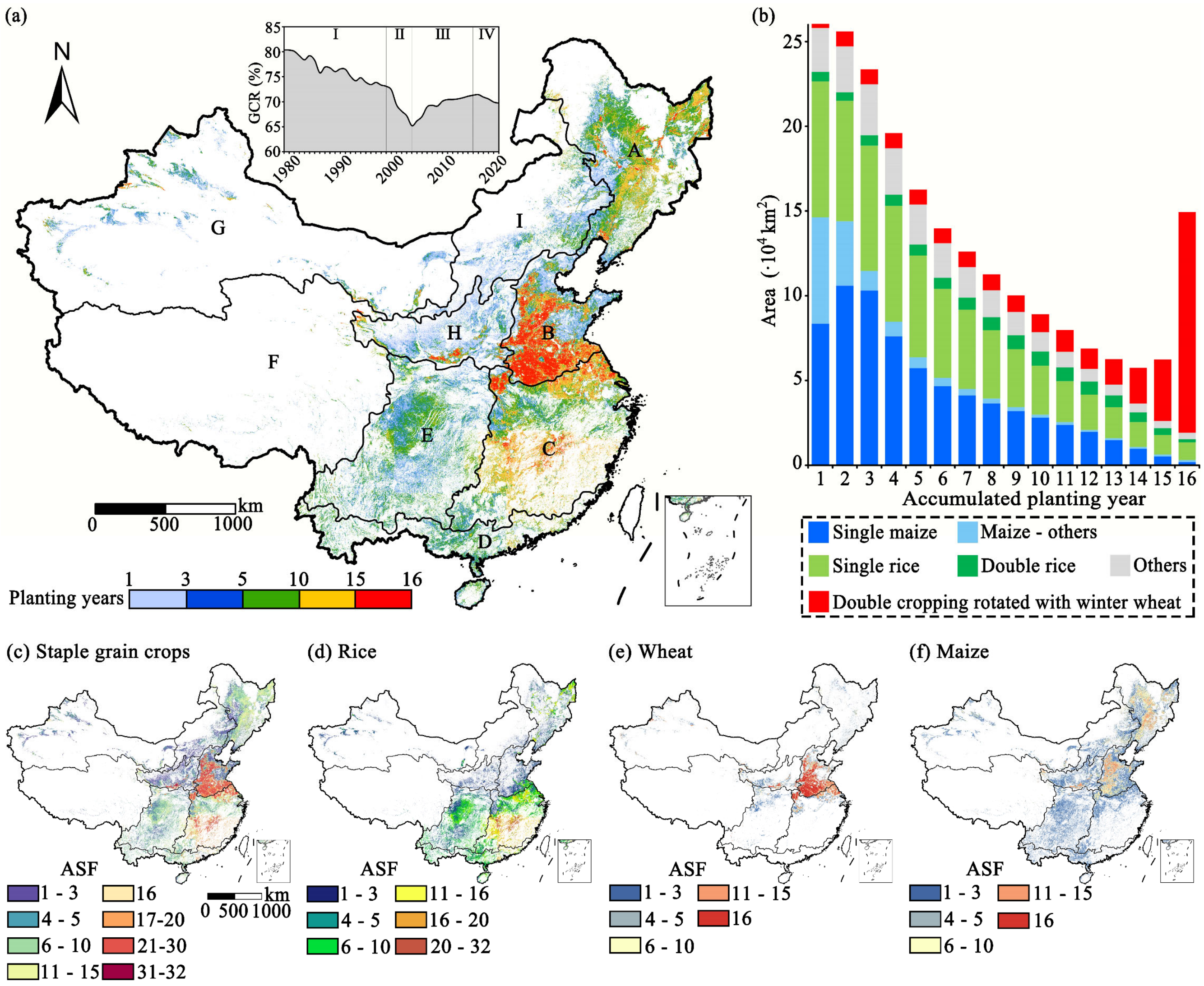


Figure 2. Maps of (a) GCR trend since 1978 and accumulated planting years of grain crops during 2005-2020, and (b) the histogram; maps of Accumulated Sowing Frequency (ASF) for (c) total staple grain crops, (d) rice, (e) wheat and (f) maize.

3.2 Capability of grain cultivation by crop types, cropping intensity and cropping patterns

The capability map of grain production was developed based on the historical grain cultivation history during 2005-2020. This map highlights that the vast majority of cropland (95.68% of cropland) in China is capable of grain production (Figure 3). There is only a small proportion of cropland that has not been cultivated with the three staple grain crops, primarily located in northwest China (Figure 3). Although 63.52% of cropland is capable of multiple cropping according to the cultivation history, only approximately two-fifths of the cropland (914,224 km^2, 40.52% of cropland) is suitable for double grain cropping (double cropping of grain rotated with non-grain crops was not included) (Figure 3(a)). It is because there is 21.68% and 1.32% of cropland capable for multiple cropping with only one cropping cycle of grain crop or no grain crops, respectively. The double grain capability map reveals an asymmetric distribution: only 13.01% of cropland in the west of the Hu line is capable for double grain cropping, which is less than one-third of the national level. The east of the Hu line is responsible for 95% of double-grain capable cropland in China. The cropland unquantified for double cropping is primarily located in northern China, influenced by biophysical conditions such as the accumulated temperature limit. However, the northern portion of the middle and lower reaches of the Yangtze River Plain stood out for its long cultivation history of double cropping patterns with only one grain cropping cycle (i.e. paddy rice rotated with other crops) (Figure 2, Figure 3).

The capability revealed by CCR varied significantly among different grain crops (Figure 3). The CCR was 76.88% for wheat, 57.05% for rice, and only 25.18% for maize. This indicates that there was a total of 1,734,600 km^2, 1,287,333 km^2, and 568,196 km^2 areas quantified for maize, rice, and wheat production in China, respectively. More than one half (54.11%) of the EGC were capable of grain production for at least two staple grain crops (Figure 3(b)). There were around one tenth of EGC quantified for any of these three staple crops (Figure 3). Cropland quantified for only one grain crop was mainly accounted by maize or paddy rice, which primarily located in the Northeast China (maize) or Southeast China (rice), respectively (Figure 3). The capability ratio of double grain cropping diversified among different grain crops and cropping patterns, which was very high for wheat (80.79%), followed by rice (48.15%) and maize (37.80%). According to the capability maps of double grain production, cropping pattern of winter wheat-maize (415,357 km^2) ranked the first, followed by double rice (335,916 km^2), rice-maize (263,273 km^2), and winter wheat-rice (144,957 km^2). There were 24.55% of double-grain capable fields (224,430 km^2) quantified for multiple double-grain cropping patterns (Figure 3).

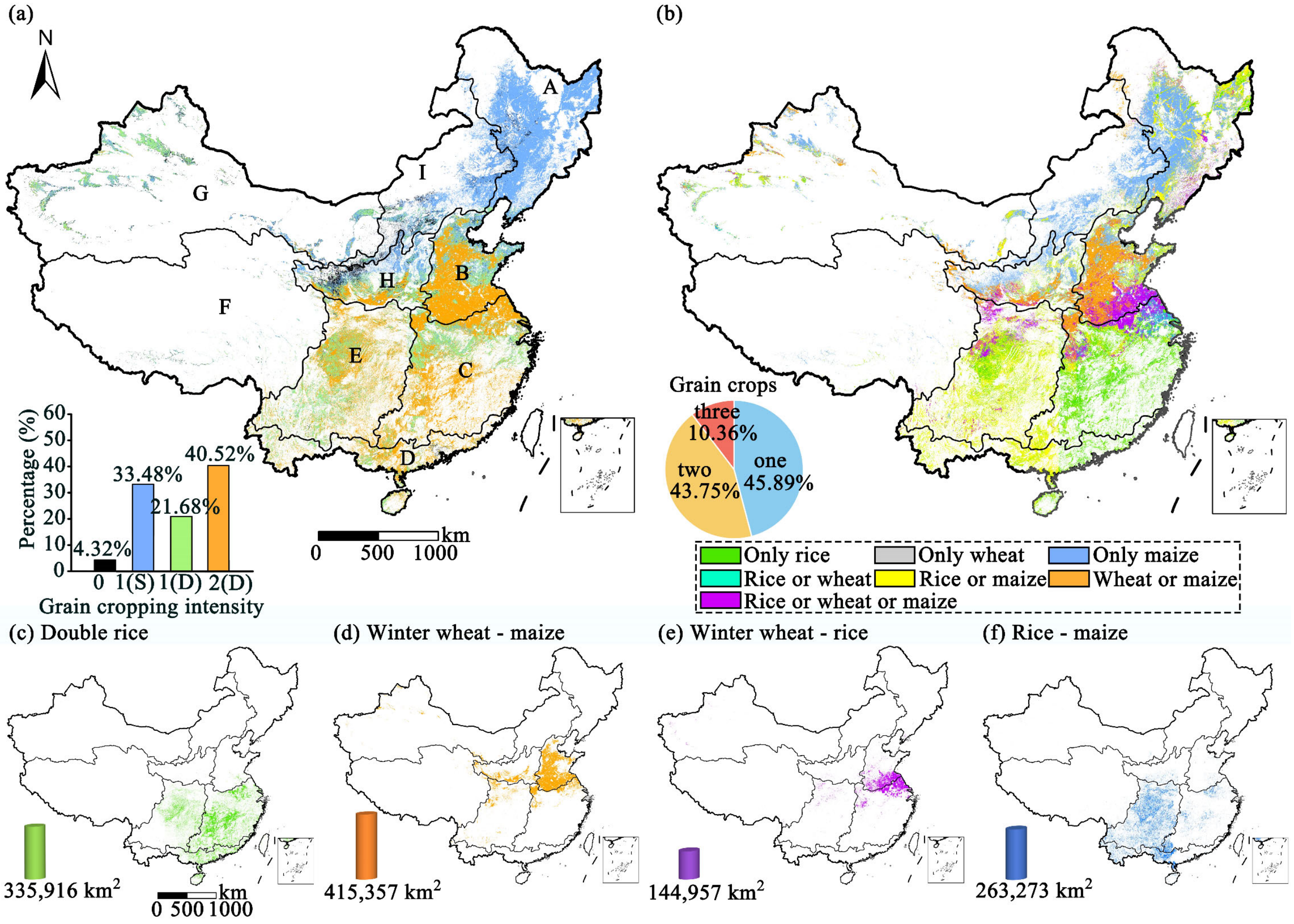


Figure 3. Maps of grain production capability on (a) grain cropping intensity, (b) three grain crop types, and for double grain cropping patterns: (c) double rice, (d) winter wheat-rice, (e) winter wheat-maize, (f) rice-maize in China, and (g) the capability of three staple grain crops and double cropping patterns in China.

Notes: 0, 1(S), 1(D), 2(D) represented areas unquantified for grain production, capable for single grain cropping, for double cropping with only one grain cropping cycle, and double grain cropping, respectively.

3.3 Quantifying NGP based on gaps between reality and capability of grain cultivation

Changes in grain production in China have been specific to different regions and periods over the past few decades. In 2020, the top three agricultural regions were Northeast China, North China Plain, and the Middle and lower reaches of the Yangtze River plain (Figure S2). These three key agricultural regions (regions A, B, C) collectively accounted for two-thirds of the national grain production in 2020. The Northeast China and North China Plain achieved substantial growth in grain production. Meanwhile, the southern China witnessed a gradual slowdown in grain production during the past few decades. Therefore, the gravity center of grain production in China has been continuously moving northeastwards since the 1980s (Figure S2). During the period from 1980 to 2005, the gravity center shifted northeastwards for 136 km, starting from Zhumadian city (113.7458°E, 32.8954°N) in Henan province, as estimated by the total grain yields at the provincial level (Figure S2). Subsequently, from 2005 to 2020, the gravity center further traveled northeastwards for 145 km, transitioning from Taikang county of Henan province (115.0032°E, 34.1764°N) in 2005 to Heze county of Shandong province (115.8202°E, 35.38751°N) in 2020, as determined by the actual distribution maps of grain crops (Figure S2). The northeastward shift of the gravity center of grain production can be attributed to the increase in grain production in the Northeast China Plain and the strengthened NGP in southern China during the past two decades. The significant role of the Northeast China Plain has become more pronounced compared to Northern China, especially considering that the NGPR values in three northern regions (regions G-I) were around 80% or above (Figure 4).

The extent of the NGP, as revealed by the NGP Rate (NGPR), has shown significant variations over the past few decades (Figure 4). During the middle 2000s, the NGPR was high, but it lessened in the middle 2010s, only to enhance again in recent years. Specifically, at the national scale, the NGPR declined from 57.18% in 2005 to 50.64% in 2015 and then increased to 55.36% in 2020 in China. Throughout the study period (2005-2020), six agricultural regions (regions E-I) consistently exhibited high NGPR, with agricultural region I reaching an NGPR of over 80% in 2020. On the other hand, the three major agricultural regions (regions A, B, and C) generally illustrated lower NGPR compared to the national average (Figure 4). Northeast China experienced the most noticeable changes in NGP processes since 2005. The NGPR was 58.94% in 2005, but it significantly reduced by one-third to 38.20% in 2015. However, by 2020, it had increased to 44.08%. Similarly, the Middle and lower reaches of the Yangtze River plain also exhibited a remarkable enhancement in NGPR during the recent years (2015-2020). In contrast, the North China Plain consistently had a low NGPR (around 34-35%) over the past two decades, compared to the other major agricultural regions (regions A and C). The NGP process in 2020, as revealed by NGPR, demonstrated a south-north contrast pattern compared to that in 2005: it aggravated in South China and lessened in North China (Figure 4).

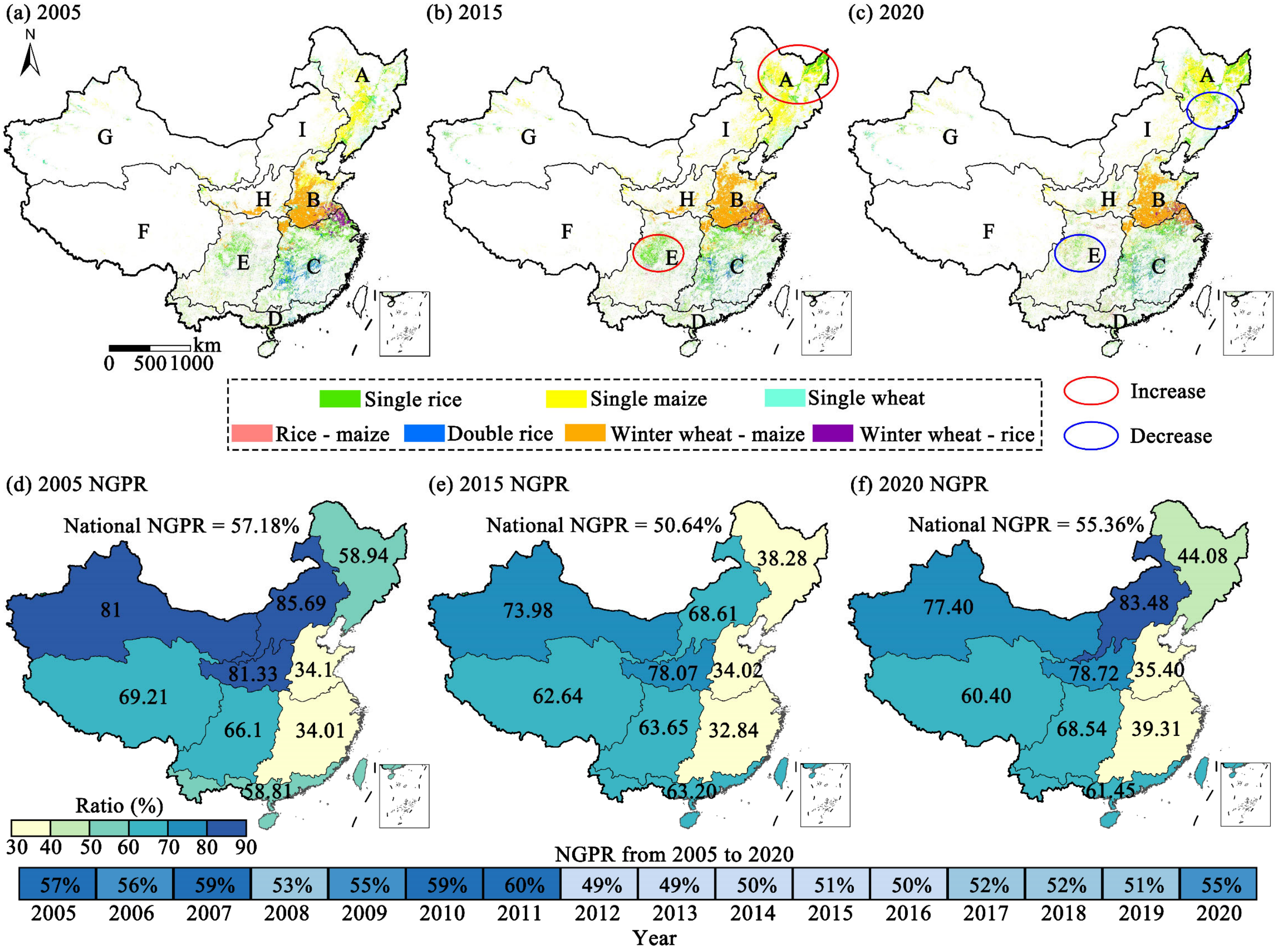


Figure 4. Maps of grain cropping patterns and NGPR in China in (a, d) 2005, (b, e) 2015 and (c, f) 2020.

Notes: the red and blue ellipses represented increase or reduction in grain cultivation, respectively.

In this study, we quantified the NGP process across conterminous China by analyzing the grain production gaps between reality and capability. The national gap in total sown area for grain cultivation was found to be 1.86 million km^2, which amounted to 2.5 times the actual sown areas of grain crops in 2020 (RCRS=40.18%). This production gap was primarily due to reductions in cropping density and intensity of grain production. Specifically, less than one-half of suitable cropland was cultivated with grain crops in 2020 (RCRE=46.65%). Among these, around one-quarter of the cropland suitable for multiple grain cropping was utilized in 2020 (RCRI=24.89%) (Figure 5). Similar to NGPR, the NGP quantified by gaps also demonstrated an east-west trend in China. The grain production gap in the west of the Hu line was at least one-third higher than the national average. Specifically, the reality-to-capability ratio in the west of the Hu line was 25.78% (RCRS), 28.70% (RCRE), and 7.54% (RCRI), respectively.

These three major agricultural regions exhibited lower gaps between reality and capability of grain production (RCRS>45%) (Figure 5). Both Northeast China and the North China Plain achieved more than one-half of the capability in the total sown area for grain production in 2020. Notably, the North China Plain showed significantly higher RCRS in double grain cropping (RCRI=40.01%). On the other hand, the Middle and Lower Yangtze River plain, in contrast to what was indicated by NGPR, ranked first in NGP when estimated by the grain production gaps among these three major agricultural regions, primarily due to the distinctive gaps in double grain production (RCRI=25.46%). The other six agricultural regions illustrated many high levels of NGP compared to the national average. For instance, Southwest China, the fourth-largest agricultural region, obtained less than one-third of its capability in grain production (RCRS=30.23%). The most serious NGP region was found in Inner Mongolia and along the Great Wall (RCRS<20%) (Figure 5). At the national scale, more than half of the cropland experienced NGP, with one-quarter having double-grain capability.

The quantification of NGP based on grain production gaps revealed significant variations among different grain types and cropping patterns. Maize exhibited the most serious extent of NGP, with only 29.14% of suitable areas cropped, followed by rice with 34.88%, and wheat with 50.13% (Figure 5(b)). Among the double grain cropping patterns, the cropping pattern of double rice experienced the most drastic changes, with less than one-tenth (7.24%) of its capability implemented in 2020 in China. In contrast, the cropping pattern of rice-maize showed a much higher RCRS (17.65%) compared to double rice (Figure 5). The double cropping pattern of winter wheat-maize emerged as the stabilizing factor for grain production, with the lowest gaps between reality and capability. More than one-quarter (27.30%) of suitable areas were cultivated with winter wheat-maize in 2020 (Figure 5). Conversely, the cropping pattern of winter wheat-rice exhibited more significant changes compared to winter maize, with only half of the reality to capability ratio (13.94%) of winter maize (Figure 5).

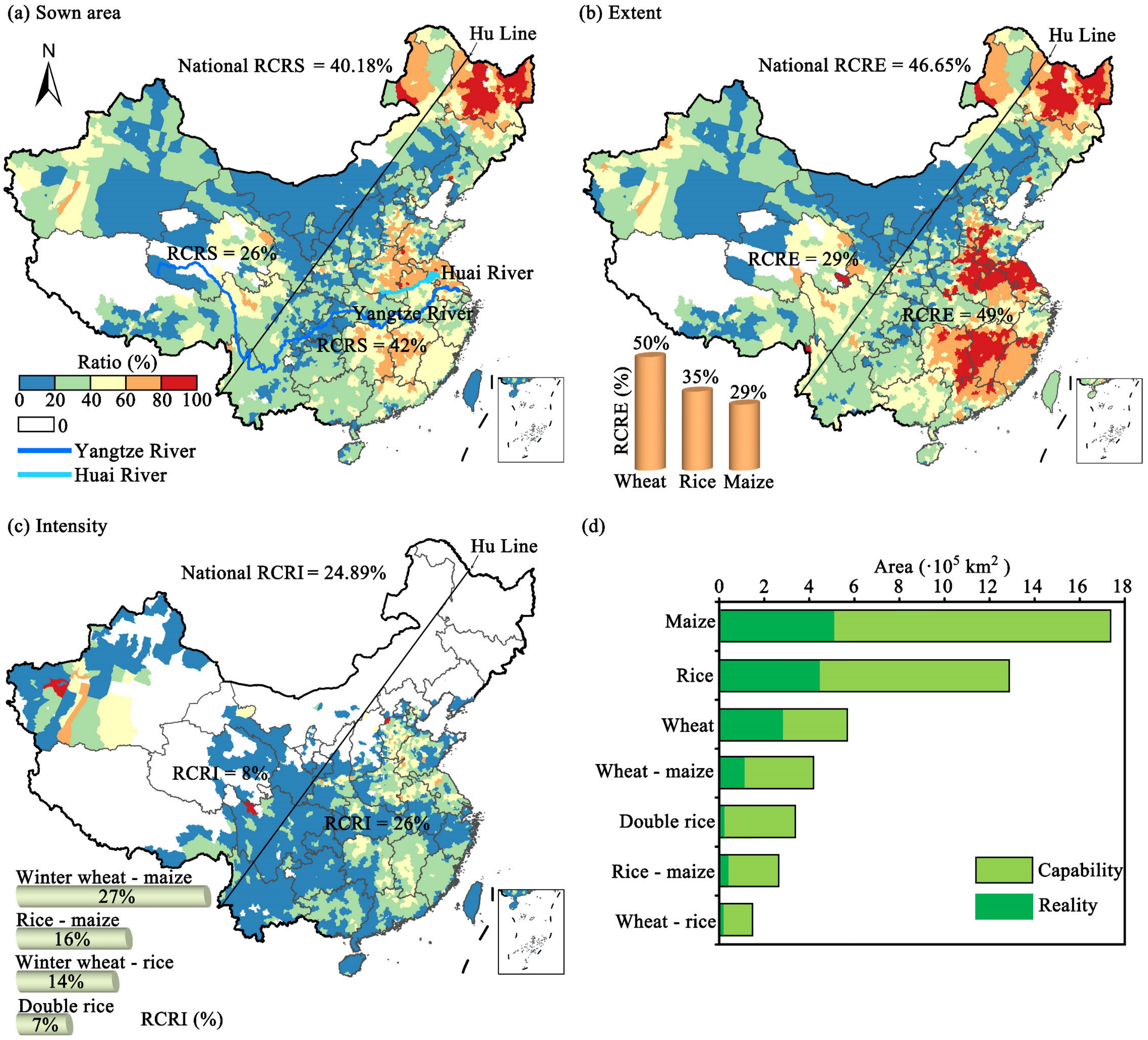


Figure 5. Maps of reality to capability ratio regarding (a) sown area (RCRS), (b) extent (RCRE), (c) intensity (RCRI) at the county level and (d) the capability and reality of sown area of different grain crops and double grain cropping patterns.

At the national scale, China experienced a grain production gap of 1,838,262 km^2 in 2020. Among the regions, Southwest China contributed to the largest share of the national grain gaps, accounting for 25.00%, followed by the Middle and lower reaches of the Yangtze River Plain, the North China Plain, and Northeast China, which accounted for 20.87%, 14.32%, and 9.87% of the national grain production gap, respectively (Figure 6, Figure S2). To close the grain production gaps, both grain expansion and grain cropping intensification play crucial roles. At the national level, grain expansion and intensification accounted for around three-fifths (62.26%, 1151,773 km^2) and two-fifths (37.34%, 686,489 km^2) of the grain production gaps, respectively. The Huang-Huai-Hai region and the three southern regions (C, D, E) are responsible for the majority of the total grain production gaps, with 67.75% of the gaps, and 92.51% of the grain gaps by intensity can be filled by these regions, which are capable of double grain cropping (Figure 3). Among these four regions (B-E), cropping intensification plays an equally significant role in filling the grain gaps. Roughly one-third of the national grain gaps resulting from cropping intensity can be filled by adopting double grain cropping practices, such as double rice, in the Middle and lower reaches of the Yangtze River plain (Figure 3, Figure 5). However, if grain expansion is not allowed based on the distribution map of grain crops in 2020, an additional 478,549 km^2 of grain sown areas (38.76% of the sown area in 2020) can be achieved through grain cropping intensification.

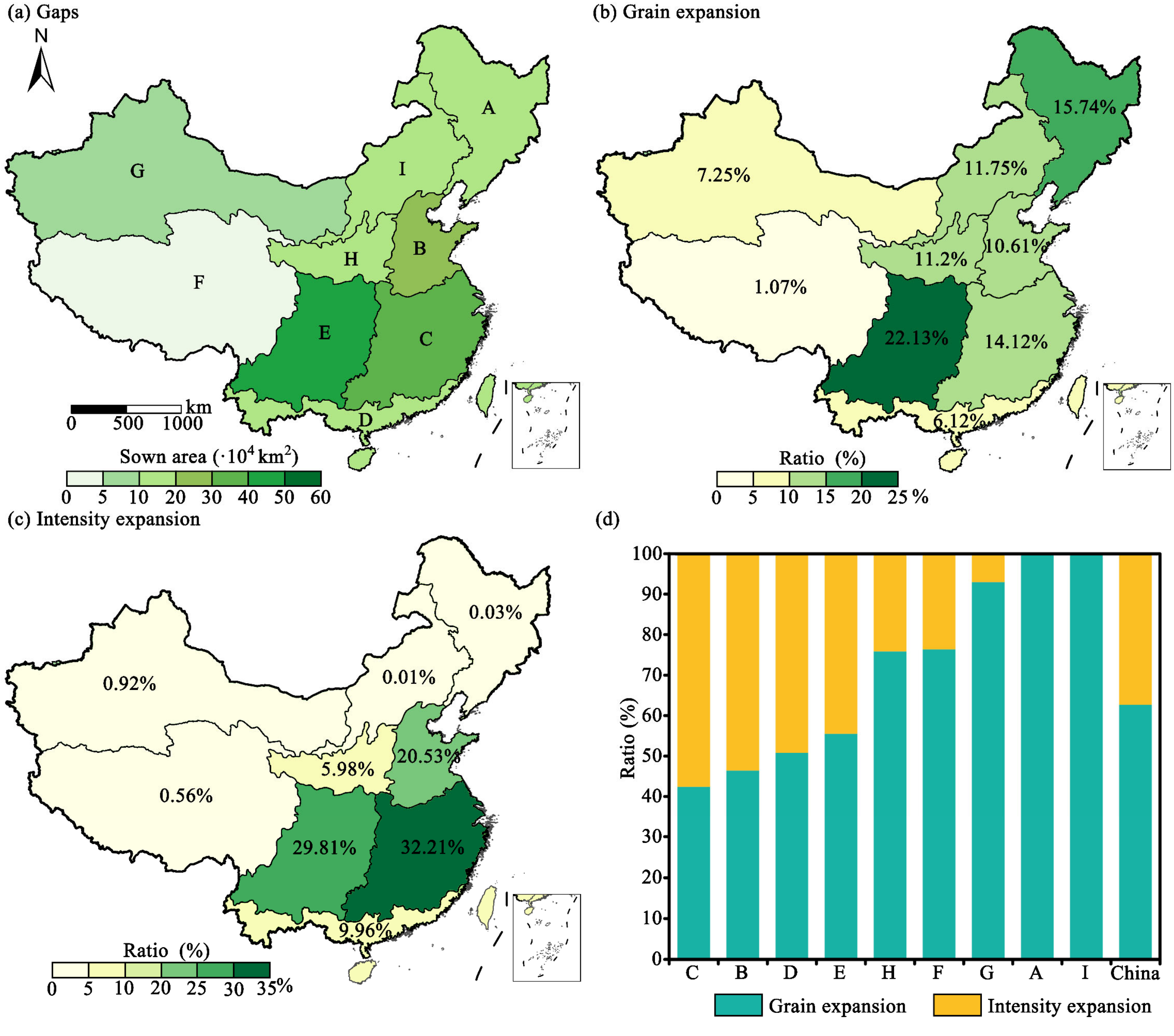


Figure 6. Map of grain cultivation gaps across different agricultural regions and municipality: (a) total gaps of sown area, (b) gaps from grain expansion, (c) gaps for intensification, (d) the proportion of grain intensification to cultivation gaps.

3.4 Unbalanced NGP Patterns shaped by urbanization, cropland fraction and topographic conditions

The extent of the NGP was found to be influenced by cropland fragmentation, topographic conditions, and climatic factors (Figure 7). As the degree of cropland fragmentation increased, the NGP process accelerated. Specifically, the

NGPR steadily enhanced from 48.95% to 66.35% as the cropland fragment increased from 10% to 90%. Moreover, the NGP level was significantly lower in plain areas (NGPR=47%) or plateaus (NGPR=51%) compared to mountains and hills (NGPR=66-69%) (Figure 7). Furthermore, the NGP level was notably lower in humid and semi-humid regions compared to arid or semi-arid regions (NGPR=83%). Lower NGP levels were commonly observed in humid plains with lower cropland fragmentation, which was consistently confirmed by these four NGP indicators (NGPR, RCRE, RCRI, and RCRS) (Figure 7).

The NGP level showed a close association with the distances to the nearest cities (municipal cities and above). The key NGP frontiers shifted from remote regions in the middle 2000s, to peri-urban and rural region in 2020 (Figure 7). The NGPR in peri-urban regions continuously enhanced from 58% in 2005 to 62% in 2015 and 69% in 2020. Conversely, the NGPR declined from 78% in 2005 to 41% in 2020 in very remote regions (⩾200 km). The reductions of NGP in remote regions was achieved mainly through grain expansion rather than intensification. This countryside shift in grain production over the past two decades is evidenced from the movement of the gravity center of grain production, which moved away from 56 km in 2005 to 63 km to city centers in 2020 (Figure 7). There were unbalanced NGP pattern shaped by urbanization: accelerated NGP in peri-urban with higher grain yield capability in contrast to expansion of grain production in remote regions with inferior capability (Figure 7).

The average grain yield capability is 885 Mt/km^2 at the national level. There is a distinctive north-south gradient in the map of yield capability per unit (Figure 7). Southern China has a grain yield capability of above 1000 Mt/km^2. However, most areas in northern China can only obtain less than 600 Mt/km^2 or even less than 200 Mt/km^2 due to its limited capability for grain production by single cropping (Figure 7). The yield capability is closely related to urbanization. The yield capability per unit is above 900 Mt/km^2 within distances of less than 70 km but reduces to less than 700 Mt/km^2 in remote regions 130 km away from the nearest cities. The decay of yield capability with distances to the nearest cities is accounted for by the capability ratio of double grain, which declined from above 60% within 70 km to less than 25% after 130 km (Figure 7).

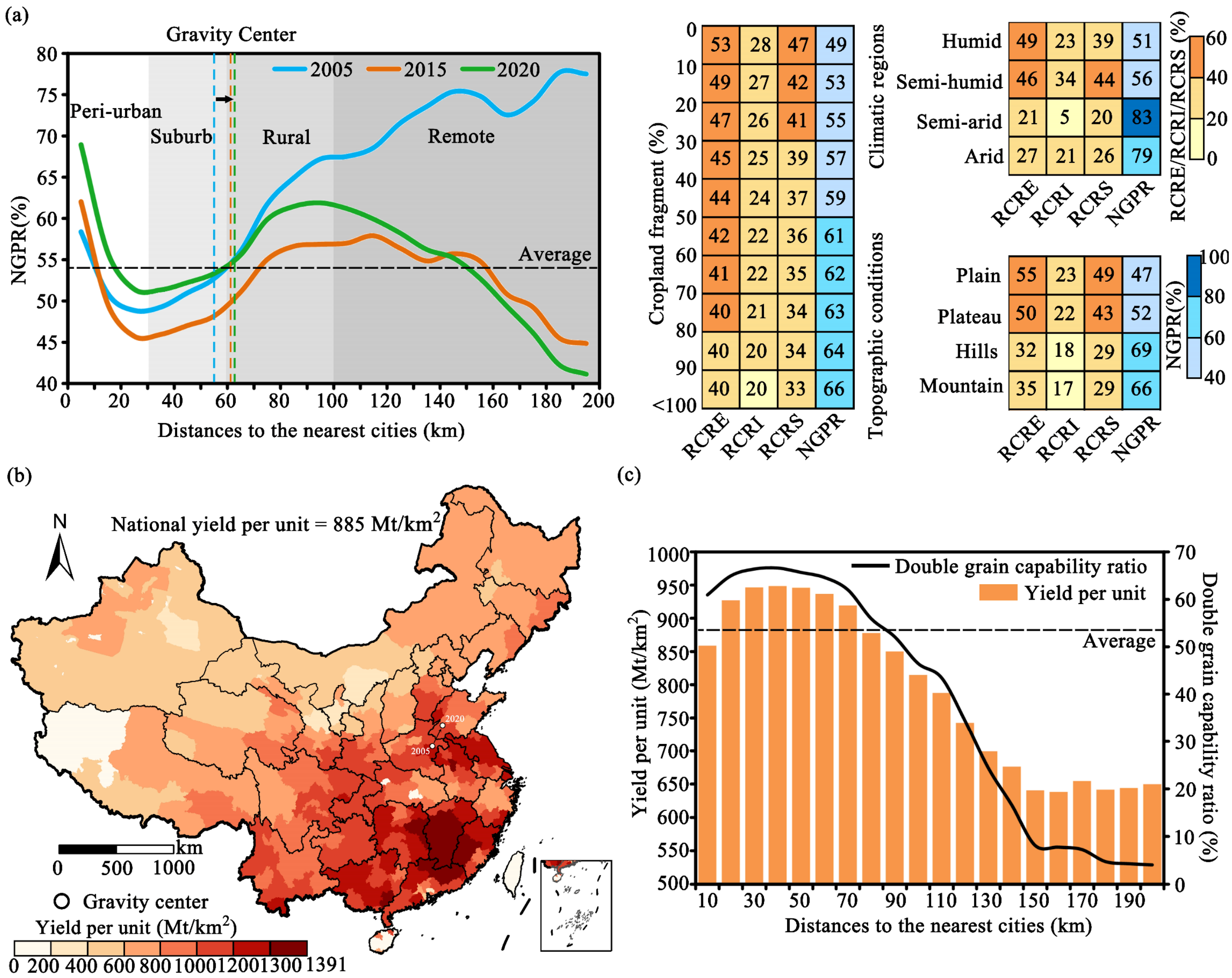


Figure 7. Changes in NGP indicators with (a) the distances to the nearest cities, cropland fragment, landform and climatic regions; (b) grain yield capability per unit at municipal level and movement of gravity of grain production from 2005 to 2020, and (c) decay of grain yield capability per unit and double grain capability ratio with different distances to urban.

3.5 Astonishing grain yield capability enabled by double grain cropping patterns

The potential yields for grain crops amounted to 1996.77 million tons, after filling the grain production gaps with the capable extent and intensity (Figure 8). This represents a substantial increase, with the potential for grain production to triple (3.29 times) compared to the reported grain production in 2020 (606.78 million tons). The RCRY at the national scale is only 30.39% (Figure 8). Henan and Jilin provinces ranked as the top two (50%), followed by Heilongjiang, Shandong, and Hebei provinces (40%). In contrast, less than one-fifth of the grain yield capability was actually achieved in any of the provinces in southwest and southern China (RCRY<20%). These regions are well quantified for intensification enabled by rice cropping patterns (double rice, rice-maize) (Figure 3). Notably, there were four provinces/directly-controlled municipalities with an RCRY lower than 10%, including Guizhou (10%), Beijing (10%), Qinghai (7%), and Xizang (Tibet) (4%) provinces (Figure 8).

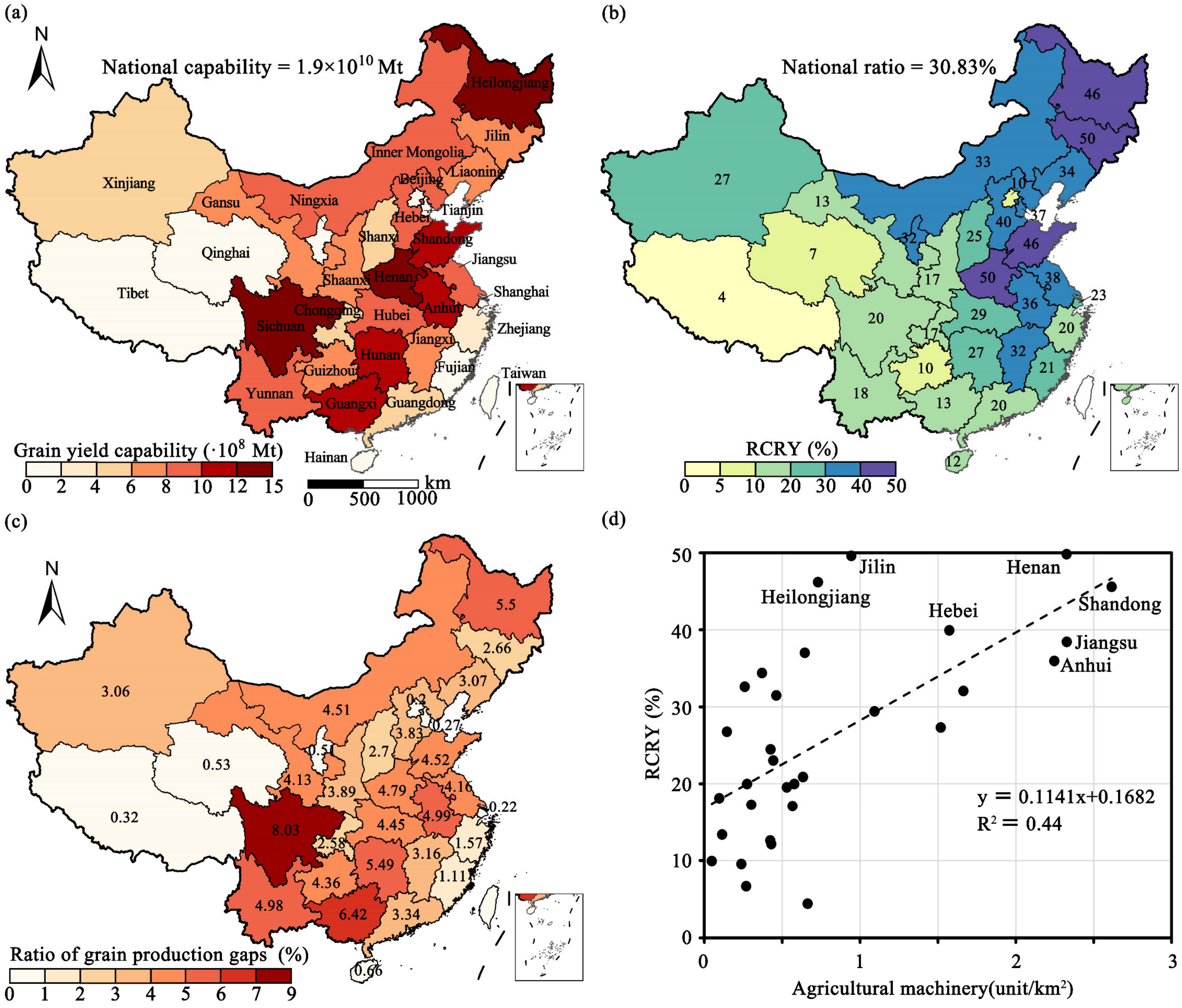


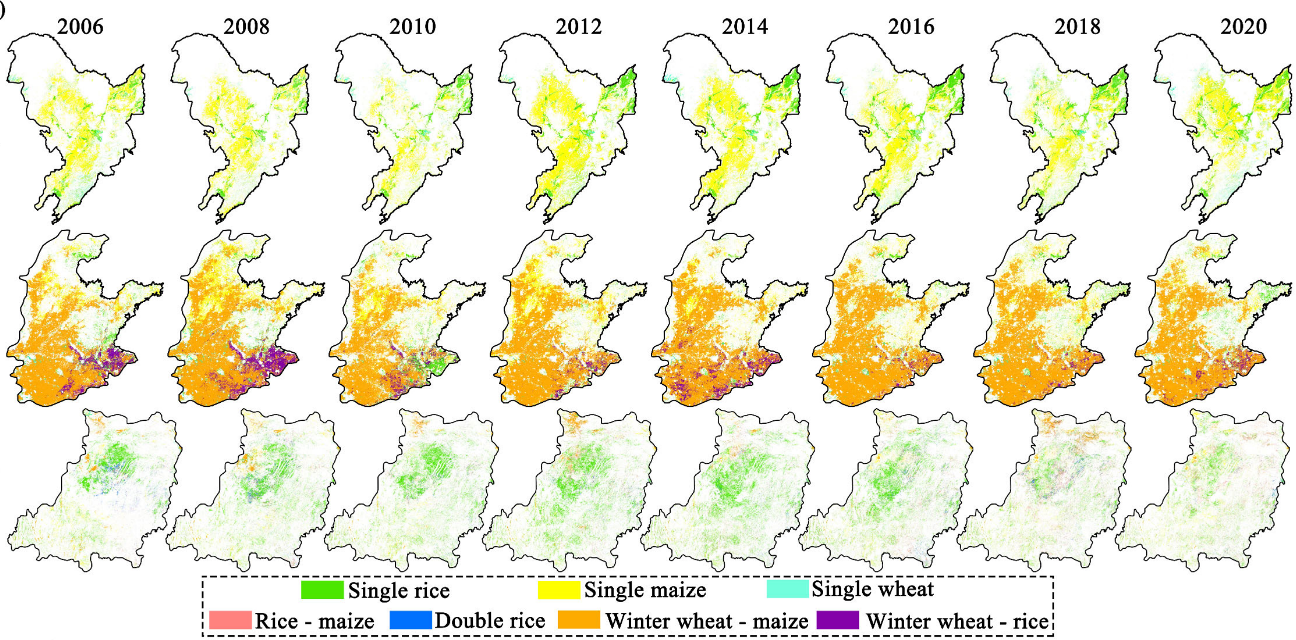
Figure 8. Maps of (a) total grain yield capability, (b) reality to capability ratio, (c) proportions of grain production gaps at provincial level, and the relationship between RCRY and agricultural machinery at provincial level.

There will be an additional 1.4 billion ton of grain if the capability is fully implemented, two provinces in southwest China (Sichuan and Guangxi) ranked the top two in filling these gaps of grain production (Figure 8). The grain production gaps between reality and capability were primarily located southern China. Specifically, the production gap in Southwest China could be filled by joint efforts of grain expansion and intensification (Figure 6), while that in the middle and lower reaches of the Yangtze River plain could primarily be filled by intensification associated with rice cultivation (double rice, winter wheat-rice) (Figure 3). However, achieving this increase poses challenges related to smallholder farms and cultivation history, especially in areas uncropped by grain for an extended period. There was a series of constraints related to cropland fraction, topographic conditions, the levels of agricultural machinery and irrigation, lack of agricultural labors along with rapid urbanization (Figure 7, Figure 8, Figure S3).

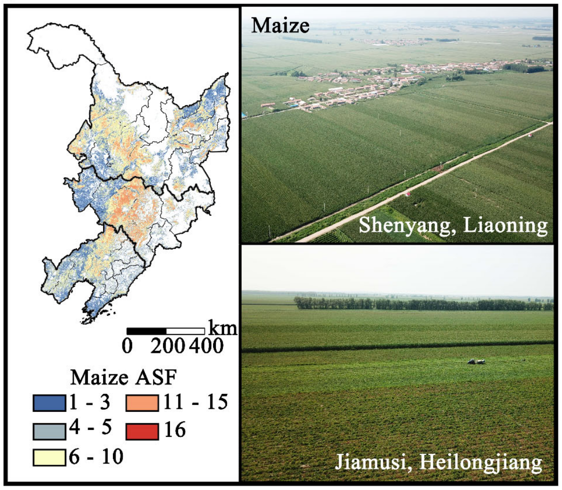
Recovering grain production is challenging in Southwest China, which is characterized by mountainous and hilly regions (Figure S3). Especially, over 85% of cropland in Southwest China has not been cultivated by grain crops for over 8 years during 2005-2020 (Figure S3). Recovering double rice cropping in southern China also faces several constraints. Firstly, the labor-intensive nature and low profitability of rice cultivation discourage its practice, especially in peri-urban regions experiencing rapid economic development. Secondly, the susceptibility of early rice to climate changes, coupled with its lower quality, diminishes the attractiveness of double rice cropping. Lastly, if cropland remains uncultivated for several years, it may no longer be suitable for rice cultivation due to the stringent requirements of cropland quality, including soil types and irrigation conditions, in addition to these aforementioned reasons (Figure 9).

The investigations on historical grain cultivation using annual grain maps highlights the critical roles of the three major agricultural regions (A-C) in producing staple grain crops in China during the past two decades (Figure 9). These three regions accounted for over 80% of the frequently grain-cropped areas (APY >8 years) (Figure 2). Notably, two major rice-productive provinces, namely Hunan and Jiangxi, in Region C, were responsible for four-fifths of the regularly rice-cropped areas (ASF>16) in China. Additionally, Agricultural region B played a significant role in contributing to 71% of the national wheat regularly cropped areas (ASF>10) and 84% of the national maize cropped areas (APY>10), along with region A (Figure 9, Figure S3). This study further disclosed the significant role of winter wheat in stabilizing grain production through double cropping rotated with maize or rice. The capability ratio of double grain cropping was around 40% based on historical cropping pattern datasets, which was mainly accounted by winter wheat maize and double rice (Figure 2, Figure 9). Winter what dominated the continuously grain-cultivated areas (6.63% of cropland in China), while having a capability ratio only one-third of maize.

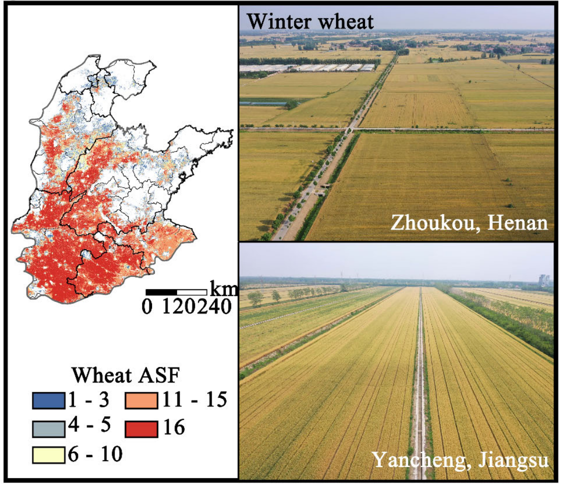
(a)



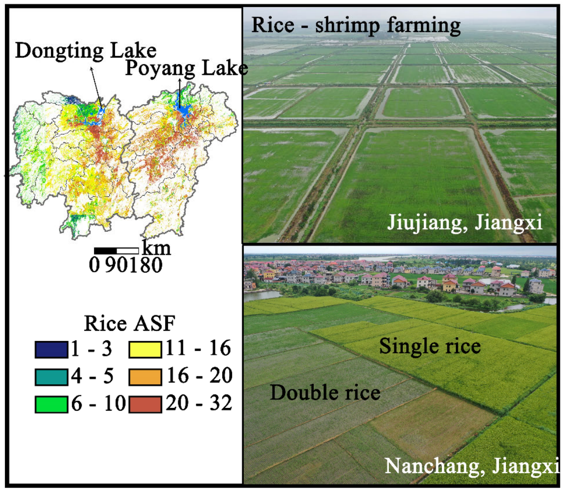
(b) Region A



(c) Region B



(d) Hunan and Jiangxi provinces in region C



(e) Field photos of NGP process

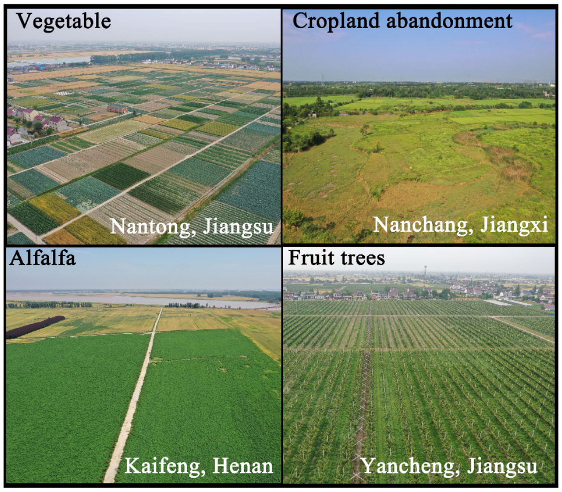


Figure 9. Maps of (a) historical grain cropping patterns in three major agricultural regions (A, B, C), (b, c, d) some snapshots of grain cultivation history in key agricultural regions and (e) some field photos of NGP processes.

4. Discussion

4.1. Lessons learned from historical annual grain cultivation

There have been ongoing debates regarding the potential for further increasing global crop yields, as evidenced by related studies (Grassini et al., 2013; Liu et al., 2021; Mueller et al., 2012; Ray et al., 2012; Yuan et al., 2021). While many studies have primarily focused on yield gaps concerning the differences between actual yield and potential yield per unit in single cropping (Van Ittersum et al., 2013), it is important to recognize that crop production can also be boosted by optimizing the spatiotemporal arrangement of individual crops within cropping systems (Guilpart et al., 2017; Zhang et al., 2021). An effective example of increasing grain production involves transitioning from single rice cultivation to a double cropping system of winter wheat and paddy rice rotation. Rice intensification has emerged as a promising approach for enhancing rice production in Asia (Jain et al., 2023), particularly in regions where multiple cropping and cropping intensity gaps exist (Guilpart et al., 2017) To achieve increased food production, a prudent strategy involves agricultural intensification while considering the environmental implications of agricultural expansion (Garnett et al., 2013; Upcott et al., 2023). In this context, agricultural intensification becomes a pivotal step towards sustainable agriculture, enabling us to meet the growing demands for food production (Rudel et al., 2009).

Yield gap assessments for sustainable intensification require site-specific priority cropping systems with descriptions of crop types, cropping intensity, and other related cropping practices (Cassman and Grassini, 2020). Cropping intensity gaps are conceptualized as the differences between the potential temperature or precipitation-limited cropping intensity and the actual cropping intensity implemented by farmers (Wu et al., 2018). However, the potential for enhancing cropping intensity is probably much smaller than previously estimated since it might be further limited by other factors such as soil conditions and the specific requirements of different crops (Waha et al., 2020). Updated annual cropping intensity maps are essential for promoting sustainable agricultural intensification and establishing reasonable agricultural structures (Waha et al., 2020). The ability to map and characterize cropping patterns and rotations enables targeted mitigation measures for addressing potential environmental risks (Upcott et al., 2023). Understanding how grain production changes across space and time is crucial for realizing sustainable food systems (Alemu, 2022; Ayanlade and Radeny, 2020; Gumma et al., 2014). However, there have been no systematic national-scale investigations on grain or no-grain production with spatiotemporal-specific information on crop types, mainly due to a lack of data sources, which hinders our understanding of implementing target-specific policies (Liang et al., 2023).

Our study framework addresses these issues based on long-term datasets of historical grain crop cultivation practices with detailed information on grain crop types, rotation sequences, and cropping intensity in China. China has the largest multiple cropping areas dominated by smallholder farms in the world (Wu et al., 2018). Cropping intensity experienced a remarkable increase during the late 20th century but a slight decline during the early 21st century (Qiu et al., 2017a). Stable agricultural systems are fundamental for the reliability of food security (Egli et al., 2020). Ensuring grain supply stability in China should be achieved by sustaining the grain yield capability on existing cultivated land

(Zhong et al., 2022). Food demand in China is projected to continue growing in the coming decades (Zhao et al., 2021). However, knowledge of the capable and actual grain cropping intensity in China remains very limited. This study found that the proportions of cropland quantified for multiple cropping were 80% when considering temperature limitations using the FAO/IIASA Agro-ecological Zones (AEZ) model (Fischer et al., 2002), but declined to 66% based on historical cultivation datasets of multiple cropping. The production systems of staple grain crops in China still have a large potential for improvements, which should be implemented through crop-specific and region-targeted strategies (Zhuang et al., 2022).

Paddy rice, maize, and wheat are the most important staple grain crops in the world (Gumma et al., 2014). These three staple crops account for 97% of total cereal areas in China and roughly 80% of global cereal areas (FAO, 2019). Rice, in particular, feeds nearly half of the global population, making increasing rice production essential for ensuring food security (Yuan et al., 2021). Wheat serves as the main staple food for over one-third of the world's population, with China consuming roughly one-fifth of global wheat production (Grote et al., 2021). Wholegrain cereals like wheat and maize offer significant health benefits (Poole et al., 2021). For the future, cropping systems need to produce more grain while minimizing negative environmental impacts (Alemu, 2022; Ambikapathi et al., 2022). Maize has played a diverse and increasing role in global agricultural systems, serving as animal feed, an essential food source, and for various non-food uses (Erenstein et al., 2022). Due to its multiple functions, maize is projected to be the most widely grown and traded crop in the coming decades (Erenstein et al., 2022). Collectively, the world's staple grain crops, namely rice, wheat, and maize, provide more than 40% of the world's calories (Jain et al., 2023).

There is growing concern about the future sustainability of rice cropping systems (Yuan et al., 2021). Over the past two decades, rice cropping systems in China have undergone significant changes in distribution and cropping intensity. Previous studies have highlighted opposing trends in different regions. While there was a significant decline in paddy rice cultivation in the Yangtze Plain of southern China, there was aggressive expansion in Northeast China (Luo et al., 2020; Zhang et al., 2020). The reduction in double rice cultivation has led to a lessening of rice cropping intensity in southern China (Lai et al., 2020). Some studies have suggested that food sufficiency in China could be achieved through optimized management of maize production (Liu et al., 2021). The past two decades have witnessed diverse spatial and temporal patterns of grain production, with particular attention to the productive cropland in warm and humid regions, such as southern China (Kong, 2014). To ensure sustainable grain production, various strategies are recommended. In southern China, rice production should be intensified to maximize yields. In the North China Plain, double cropping of winter wheat should be stabilized to promote reliable grain production. Additionally, maize production in northern China should be reasonably maintained (Figure 8). Targeted strategies to improve multiple cropping systems are particularly crucial in the North China Plain and Southeast China, with a specific focus on double cropping of winter wheat-rice near the Huaihe River and the Yangtze River (Figure 5). These strategies aim to enhance grain production while considering regional variations and environmental impacts.

4.2. Complex NGP patterns in smallholder agriculture and targeted regions

China, as the world's largest smallholder agriculture, has undergone significant changes in grain cropping systems in recent decades (Cui and Shoemaker, 2018; Huang and Rozelle, 2018). Understanding these change processes in agricultural systems is crucial for predicting future development trajectories and policy implications (Van Vliet et al., 2015). However, there is a lack of knowledge regarding when, where, and how grain production and NGP have evolved in China in recent years. Existing studies on China's agricultural productivity have predominantly focused on quantities of cropland, total sown areas, and yields of grain crops, using provincial or county-level statistical data (Chen et al., 2023; Ge et al., 2018; Lai et al., 2020; Leng et al., 2021; Zhong et al., 2022). The commonly applied non-grain ratio, based on agricultural census data, may introduce biases and prejudices in multiple-cropping regions (Cheng et al., 2022). Only a few recent studies have investigated the non-grain phenomenon based on limited spatiotemporal data of specific crop types, regions, or years (Liang et al., 2023; Yang and Zhang, 2021; Zhang et al., 2023). The accessibility of data associated with food production is of utmost importance (Fróna et al., 2019). However, studies exploring the NGP process using long time series data at the regional or national scale are rarely seen (Zhang et al., 2023). More comprehensive and detailed spatiotemporal data are needed to better understand the dynamics of grain production and NGP in China.

This study presents systematic investigations on grain cropping history based on annual spatiotemporal cropping pattern datasets during the past two decades. Surprisingly, the NGP was found to be far more extensive than initially expected, with an NGP rate of over 50%, consistent with related studies using 1 km geospatial datasets (Zhu et al., 2022). The NGP rate in China, as estimated from grain-cultivated maps, was much higher than previous results based on statistical data (NGPR=27%) (Kong, 2014). Notably, the NGP rates were significantly higher in mountainous and hilly regions with fragmented cropland, which aligns with related studies based on statistical data (Guo et al., 2023). Furthermore, this study revealed reductions in grain production under unfavourable conditions, attributed to both a lessened grain cultivated extent and cropping intensity.

The major drivers of crop changes include urbanization, changes in cropping intensity, and cropland abandonment (Luo et al., 2020; Qiu et al., 2020). Biophysical conditions play a crucial role in shaping the NGP process (Zhang et al., 2023), while financial factors also directly contribute to about half of the crop changes (Mehdi et al., 2018). During the period 2003-2015, grain sown area and output steadily increased, even though the percentage of profits from crop cultivation in total household income dramatically declined (Lai et al., 2020). Notably, this study found that the steady increase in grain production during 2005-2015 primarily occurred in rural regions (Figure 7). In remote regions, intensified grain production can be attributed to improved agricultural management, such as increased utilization of agricultural machinery and strengthened irrigation practices. Grain crop production appears to be more significantly influenced by socio-economic conditions, including agricultural subsidies and investments in machinery, compared to non-grain crops (Qi et al., 2023). The continuous increase in grain production in remote regions partly compensates for the intensified NGP in peri-urban regions.

This study revealed a notable northeast shift of grain production at a rate of 15 km per year, continuously moving into drier and colder regions in China since the 1980s (Figure S2). This shift was primarily driven by significant reductions in rice cultivation in southern China and the expansion of maize production in Northeast China (Figure 4). The extent of the northeastward movements of grain production was greater than previously estimated based on total cropland (Wang et al., 2018; Zhong et al., 2022). Over the past few decades, China's grain production history has undergone significant changes (Lai et al., 2020). Maize harvesting areas witnessed substantial expansion in major maize cultivation regions across China from 2005 to 2015 (Luo et al., 2020; Qiu et al., 2018). However, such agricultural expansion and intensification in northern regions pose critical challenges concerning ecosystem services and local livelihoods (Meyfroidt, 2021). Crop yield in Northeast China and the North China Plain is more vulnerable to reductions caused by droughts (Shi et al., 2021). The northeastward shift of grain production presents increasing challenges for sustainable grain production in the future, including the transportation of food over longer distances from northern China to the densely populated southern regions and a rise in water consumption associated with grain production (Yu et al., 2023).

4.3. Challenges for sustaining grain production in China and possible solutions

The Chinese government has taken significant steps to ensure food security through a series of policy measures (Bryan et al., 2018; Huang and Yang, 2017). Notably, China's agricultural policy underwent a transformation from taxing to subsidizing and protecting agriculture starting from 2006 (Huang and Yang, 2017). While agricultural intensification remains a priority, maintaining a stable cultivation area for grain crops is equally vital for sustaining overall grain production. However, in recent years, several factors have led to the widespread conversion of cropland to non-grain production due to accelerated urbanization, continuous loss of labor, and an aging rural population (Chai et al., 2019; Su et al., 2020). The allure of grain production has diminished for farmers, given its lower profits and high labor demands (Yuan et al., 2021). Furthermore, cropland fallow and abandonment have exceeded expectations, particularly in mountainous or hilly regions and peri-urban areas (Qiu et al., 2022b). Interestingly, the NGP areas have witnessed remarkable intensification with clustered spatial patterns over the past two decades, and this trend is projected to continue (Liang et al.; Zhao et al., 2017). In response to these challenges, the General Office of the State Council of China issued the "Opinions on Preventing Non-Grain Activities and Stabilizing Grain Production of Cultivated Land" in 2020 and implemented a series of stringent measures to stabilize grain production (Cheng et al., 2022; Zhang et al., 2023). These measures aim to address the issue of non-grain activities on cultivated land and bolster efforts to ensure a consistent and secure grain supply in the country.

This study indicated that grain production could be tripled by optimizing the production capability, with roughly two-fifths achieved by filling the cropping intensity gaps at a national scale. Improvements of crop production varied by cropping systems, which were further limited by biophysical constraints (Bryan et al., 2018). As urbanization continues and the agricultural population ages, the trend of de-intensified rice cropping patterns or non-grain production is expected to persist (Kriebs, 2023). To sustain these traditionally rice cropping regions effectively and ensure a robust rice supply, specific measures should be considered, such as directly-seed rice plantation, rice ratooning, and rice-fishery farming in well-irrigated croplands. Moreover, a strategic shift towards non-rice crops, such as sweet potatoes and soybeans, could also prove beneficial. These initiatives are vital for maintaining a significant rice production capacity in the region.

The findings of this study carry significant policy implications for ensuring sustainable grain production in China.

Several key measures should be taken into consideration:

Firstly, continuous support must be extended to the long-term active agricultural systems in China, particularly in key grain production regions (Figure 8). Sustaining grain production capability in these actively cropped fields forms the bedrock of food security. Hence, prioritizing the support of productive and sustainable grain production systems in these critical agricultural regions is imperative.

Secondly, targeted surveillance efforts should focus on maintaining and intensifying specific grain cropping patterns in these key agricultural regions. For instance, stabilizing grain production can be achieved by promoting double cropping of winter wheat and maize or rice. However, the lack of large-scale updated high-quality data poses a major challenge to better understanding agricultural and environmental systems and their interactions (Ortiz et al., 2021). To design effective strategies towards sustainable intensification, updated crop datasets with finer resolutions are essential.

Additionally, comprehensive planning and solutions should be devised to ensure balanced and sustainable development, taking into account regional disparities and the urban-rural discrepancy. Modernizing agricultural infrastructure, creating high-quality farmland, and increasing agricultural mechanization levels in mountainous and hilly regions are crucial steps. Encouraging farmer participation and implementing improved agricultural cropping practices, such as water-saving irrigation techniques and crops with lower water or heat requirements, will help address the challenges of grain production in China (Cui et al., 2018).

Moreover, to cope with the diminishing interest of younger generations in agriculture amid ongoing urbanization processes (Liao et al., 2022), it is of critical importance to rekindle public engagement in agricultural science. Raising awareness and fostering renewed interest in agriculture among the youth will contribute to the sustainability and growth of the agricultural sector.

4.4. Uncertainties and future works

There are some limitations and uncertainties in this study. First, the widely reported mixed-pixel problem of MODIS images may introduce uncertainties in fragmented cropland areas in mountain and hilly regions in southern China, as we considered only one major cropping pattern for each pixel. Nevertheless, the use of dense time series such as the MODIS datasets enabled long-term investigations on cropland dynamics across large regions (Estel et al., 2016). The 500m MODIS-derived cropping patterns datasets (ChinaCP) demonstrated good accuracy when evaluated against reference sites and reported agricultural census data (Qiu et al., 2022a).

Second, the reliability of the cropland map is essential for the accuracy of derived cropping pattern datasets (Zhang et al., 2021). While the 30m GlobeLand30 data achieved good performances (Chen et al., 2014), there may still be some misclassifications. Additionally, the spatiotemporal processes of grain production were based on the assumption that cropland distribution remained relatively stable during the past two decades, but there is evidence of a continuous northward shift of cropland in recent decades (Zhong et al., 2022). Consequently, the estimates of the Northeastward shift of grain production in this study are likely conservative.

Third, this study did not include cropping pattern datasets during the early 2020s (2021-2023) and other minor grain crops (i.e. millet, sorghum). Recent cropland protection policies and their influences on grain production were not fully captured in this research.

Finally, this study focused on the cultivation gaps related to the grain extent and cropping intensity and did not consider combined considerations of yield gaps and potential incoming constraints under global changes. Sustainable intensification of grain production is a complex process that involves optimal cropping practices, corresponding local biophysical conditions, and the impacts of increasing climate changes, such as extreme heat and frequent drought (Lobell et al., 2020; Pretty et al., 2018). Sustainable rice production, for instance, needs to address issues related to greenhouse gas emissions and high labor requirements (Yuan et al., 2021). Furthermore, maps of cropping intensity and crop types are critically important, and there are still significant data gaps in agricultural monitoring needs (Fritz et al., 2019). Utilizing spatiotemporal continuous grain production datasets with finer spatial resolutions and good quality would be beneficial in such future research topics.

To address these limitations, future works could be conducted to generate updated cropping patterns datasets with descriptions on multiple grain crops using remote sensing images with finer resolutions (i. e. Sentinel-1 SAR, Sentinel-2 MSI and GaoFen time series images) (Cai et al., 2023). Minor crops could play an important role in stabilizing and improving food production systems (Renard and Tilman, 2019; Rusinamhodzi et al., 2012). Further investigations on a full coverage of different grain crops (cereal crops, potato crops and bean crops) could be promoted to address the collective goals of food security, environmental consequences, and rural revitalization. There are various factors such as labor forces, economic development, and advancements in agricultural techniques, which play pivotal roles in shaping and constraining grain crop cultivation (Bentley et al., 2022). Lesson can be drawn from systematically investigating the drivers and implications of spatiotemporal changes agricultural production systems (Alemu, 2022).

5. Conclusions

The rapid expansion of Non-Grain Production (NGP) poses a growing concern for global food security, yet limited knowledge of its extent is attributed to a lack of geospatial data. This study addresses this gap by investigating the spatiotemporal patterns of grain production in China over the past two decades (2005-2020), with a focus on grain crop types and cropping patterns. Through the analysis of spatiotemporal continuous datasets, we quantify the NGP process across China, examining crop types, cropping intensity, and patterns. Our main measures, the NGP Rate (NGPR) in cropland, and the reality to capability ratio of grain production, provide valuable insights into historical grain cropping extent and cropping intensity. Although there was a declining trend in NGPR from 2005 to 2015, it has experienced rapid growth in recent years, reaching 55.48% in 2020. We find that 96% of cropland is capable of grain production, with two-fifths of it suitable for double grain cropping. However, one-third of cropland had only been used for grain cultivation for 1-3 years, primarily with single maize or rice crops. The low Rate of Cropland under Regular Grain Production (RCRS) in 2020 (40.18%) is attributed to reduced extent (RCRE=46.65%) and astonishingly low intensity (RCRE=24.89%). Closing these gaps could potentially triple grain production in China.

This study highlights diverse grain production processes among agricultural regions and cropping patterns. Maize, rice, and wheat have been cultivated in 76.88%, 57.05%, and 25.18% of national cropland, respectively. Winter wheat emerges as a crucial element in stabilizing grain production, accounting for 7/8 of continuously grain-cultivated areas (6.63% of China's cropland). However, double rice capability has been only minimally implemented in China in 2020. The unbalanced NGP patterns are primarily driven by urbanization, resulting in continuous reductions in peri-urban regions and accelerated expansion in remote rural areas. The findings from this study offer valuable insights into the spatiotemporal patterns of NGP and advocate for geographically targeted surveillance to support sustainable grain production, considering grain crop types and cropping intensity. In conclusion, this study significantly contributes to our understanding of NGP dynamics in China and provides essential information for policymakers and stakeholders to implement targeted strategies for ensuring food security and promoting sustainable agricultural practices. As we move forward, continuous efforts to collect and analyze updated geospatial data are crucial for improving our knowledge and advancing sustainable grain production practices.

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