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Reflections on China's food security and land use policy under rapid urbanization

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ABSTRACT

Food security concerns the economy, people's livelihood and social stability of a country or region. Countries around the world always put food security on their high-priority political agenda. As the most populous developing country in the world, China produces one-fourth of the world's food and feeds one-fifth of the population. Therefore, China's food security has attracted global attention. However, systematic research on China's food security is still insufficient. This study systematically reviewed the key issues facing China's food (supply) security, identified the potential factors affecting the county's grain production, and put forward countermeasures to further ensure food security. Results show that over the past four decades, China's rural population decreased significantly, and cultivated land area decreased in the south and increased in the north, and grain output risen in volatility. China's food security is latent with regional, structural and technical crises, and further ensuring China's food security is faced with many challenges. Potential factors affecting China's food security include the rapid farmland conversion, the aging and weakening of farmers, the spatial mismatch of water-land resources and grain production, the periodicity and instability of climate change, and the unbalanced spatial coupling of population, land and grain (PLG) system. Differentiated and oriented response measures to resolve regional and structural issues should be adopted to further ensure China's food security.

1. Introduction

As the old Chinese saying goes, "The State takes the people as the foundation, and the people take food as their priority". Food is the foundation of human survival and development. Food security is usually defined as a condition where all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary preferences for an active and healthy life (FAO, 1996; Pinstrup-Andersen, 2009). Food security is not only related to the security of a country, but also to world peace and social stability. The United Nations post-2015 sustainable development agenda has set the eradication of hunger as one of important targets of the 17 Sustainable Development Goals (SDGs) in 2030 (Griggs et al., 2013). The latest Global Food Crisis Report 2020 released by the Global Food Crisis Network shows that by the end of 2019, 135 million people in 55 countries and regions were in serious food insecurity (GFCN, 2020). Nearly 750 million people were exposed to severe levels of food security globally in 2019, and the number of people with food insecurity has been slowly increasing since 2014 (FAO, 2020). Globally, local food crop production can only fulfil demand for the less than one-third of the population (Kinnunen et al., 2020). Conflicts, extreme weather events, and economic turmoil have driven global food insecurity. Goals of zero hunger and no poverty by 2030 will not be achieved if recent trends continue (Bryan et al., 2019; FAO, 2020).

China is historically a country that is dominated by agriculture. As the most populous country in the world, China has largely managed to feed approximately 21% of the world population with only 9% of the global cultivated land (Carter et al., 2012; Zhou et al., 2019, 2020a). In 2019, global food production was 2722 billion kg, of which China's output was 664 billion kg, accounting for nearly a quarter of global food production (FAO, 2020). The Chinese central government has long put it high priority on the national political agenda (Khan et al., 2009; Lu

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et al., 2015). Extensive and in-depth researches have been done on China's food security status, affecting factors and challenges as well as strategies to ensure food security. It is generally believed that rapid urban expansion, land degradation, soil erosion, water shortages, international food price fluctuations and climate change threaten China's food security (Khan et al., 2009; Ye and Van Ranst, 2009; Norse and Ju, 2015; Wuepper et al., 2020; Ye et al., 2013; Liu et al., 2014a; Wang et al., 2017; Chen, 2007; He et al., 2017). China's rapid urbanization, wealth growth and health emphasis has put higher demands on food quality and security (Wu et al., 2011; Gandhi and Zhou, 2014; Lu et al., 2015; Gu et al., 2019; Han et al., 2020). The spatial mismatch between food production and cultivated land resource distribution affects China's food security (Li et al., 2017). The large-scale transfer of China's cropland to "marginal land" has also affected food security and environmental sustainability (Kuang et al., 2021). Furthermore, in recent years, rural labor forces moved to cities, resulting in the abandonment of cultivated land and the weakening of farmers, which also posed a threat to China's food security (Liu et al., 2014b, 2016). The question on who will feed China has once again aroused concern from all walks of life. Although China's food security is now guaranteed, in the long run, it still faces great challenges such as the tightening of water and land resource constraints for food production, structural shortages in food supply, and uneven regional food production (Liu et al., 2014b, 2018; Wang et al., 2018; Huang and Yang, 2017; Li et al., 2017; Zhou et al., 2020b). These existing findings have provided important support for the formulation and decision-making of China's food security policy.

Ensuring food security is a complex systematic project that involves many aspects such as population, land, technology, and management. The factors that affect food production interact with each other (Puma, 2019). As far as we know, so far, few studies have systematically elaborated on the influencing factors of China's food security, and explored the temporal and spatial coupling patterns of population, land and grain (PLG) system. Therefore, the main aim of this research was to systematically investigate the potential crises affecting China's food security. Firstly, we analyzed the potential threats to China's food security from the perspectives of the lack of a main body of food growing, the rapid non-agriculture uses of cultivated land, and the structure of food production. Secondly, based on the provincial panel data, the coupling coordination degree model was used to measure the coupling coordination degree (CCD) of China's PLG system over the past 40 years. Finally, an improved econometric model was used to identify the dominant factors affecting China's food production. Our findings would provide beneficial references for the formulation of policies to ensure food security and optimize land use in China and the world.

2. Methods

2.1. Data sources

The data used in this study included national data and provincial-scale data. The national data and provincial-level data only covered 2018 due to the availability of data. The balanced panel dataset included China's 31 provinces over the period 1978–2018 (Hong Kong, Macao and Taiwan are not included for lack of data). The data of the provincial population, rural and urban population size, the number of employments in the primary industry, cultivated land area, sown area of crops and main food crops, food output, total power of agricultural machinery and use of chemical fertilizer were obtained from the China Statistical Yearbook, China Land and Resources Statistical and China Agricultural Statistics, which are available from China's Economic and Social Bit Data Platform (https://data.cnki.net). Statistics on China's food imports and exports from 1990 to 2018 come from the China Grain Yearbook. Cultivated land occupied by construction purposes was collected from the China Land and Resources Almanac.

2.2. Methods

Trend analysis, coupling coordination degree model (CCD) and an improved Cobb-Douglas (C-D) production function were used in this study. Followed by a previous study (Cutter and Finch, 2008), the trend analysis was adopted to explore the changing trends of cultivated land area and grain output of China's 31 provinces from 1978 to 2018. A positive slope means an increasing trend for a variable, and a negative slope means a decreasing trend. When the slope is negative, the larger the value, the more obvious the downward trend, and vice versa. The CCD model and improved CD production function were explained as follows:

(1) Coupling coordination degree (CCD) model

Coupling coordination degree (CCD) is used to explore the coordination degree of interactive coupling between two or more systems (Li et al., 2012). The CCD model has been widely applied to study the relationship between ecological environment and urbanization. In this study, the CCD model was used to investigate the interactive coupling relationship between China's population, land and grain system (PLG). The model can be expressed as follows:

$$C_i = \left\{ \frac{f(x_i) \times g(y_i) \times h(z_i)}{[f(x_i) + g(y_i) + h(z_i)]^3} \right\}^{\frac{1}{3}}$$

$$\mathrm{CCD}_i = \sqrt{C_i \times T_i}$$

$$T_i = \alpha f(x_i) + \beta g(y_i) + \gamma h(z_i)$$

where C_n is the coupling degree for the *i*-th province. The $f(x_i)$, $g(y_i)$ and $h(z_i)$ are the comprehensive levels of the population (rural population), land (cultivated land) and grain (output) (PLG) systems for the *i*-province, respectively. CCD is the coupling coordination degree. The value of CCD is between 0 and 1, the larger the value, the higher the degree of coupling coordination between the systems, and vice versa. T reflects the overall development level of the PLG system. α, β and γ are the contribution of each subsystem. We assumed that each system is equally important to the coordinated development of the PLG system. Followed by a previous study (Xin et al., 2019), we used the quartile method to divide the CCD into four levels, i.e., seriously unbalanced [$0 \leq \mathrm{CCD} < 0.25$), slightly unbalanced [$0.25 \leq \mathrm{CCD} < 0.5$), barely balanced [$0.5 \leq \mathrm{CCD} < 0.75$) and with superior balance [$0.75 \leq \mathrm{CCD} < 1$).

(2) Improved Cobb-Douglas (C-D) production function

We used the improved Cobb-Douglas (C-D) production function to measure the impact of labor, land and technology inputs on food production. The standard form for the C-D production function model is given below:

$$Y = AL^{\alpha}K^{\beta}$$

where Y is total grain output; L is labor input; K is capital input; A is total factor productivity. α and β the output elasticities of capital and labor, respectively.

To further examine the effects of technology, labor and land on grain output, the total power of agricultural machinery (POWER), the number of employees in primary industry (LABOR), application amount of chemical fertilizer (FER), cultivated land (ARABLE) and planting area of non-grain crops (PANC) were incorporated into an extended C-D production function model. The extended C-D production function is specified as follows:

$$Y_{it} = AL_{it}^{\alpha}K_{it}^{\beta}C_{it}^{\gamma}T_{it}^{\delta}e^{\varepsilon_{it}+\theta S_{it}}$$

where Y_{it} is the grain yield of the *i*-th province at the *j*-th period. L is the number of employees in primary industry; K is the application amount of chemical fertilizer; C represents the cultivated land; T is the total power of agricultural machinery; and S is a control variable and reflects the ratio of non-food crops planted area to total planted area. α, β, γ, δ and θ are the elasticity for the labor force, chemical fertilizer, land, technology input and planting structure adjustment, respectively. ε_{it} is the residual term. To facilitate the estimation and hypothesis test, all variables take logarithmic form. The model can be written as below:

$$lnY_{it} = lnA + \alpha lnL_{it} + \beta \ln K_{it} + \gamma lnC_{it} + \delta lnT_{it} + \theta S_{it} + \varepsilon_{it}$$

(3) Grain self-sufficiency rate measurement

To reflect the food production and consumption of the provinces over the past years, the empirical coefficient method was used to measure the food self-sufficiency rate of China's 31 provinces. Since China has not published the data on food consumption and food trade of various provinces, in accordance with international common standards, we used the per capita food consumption of 400 kg to estimate the total food consumption of each province, and calculated the food self-sufficiency rate according to the following formula:

$$\mathrm{GSSR}_{it} = \frac{G_{it}}{P_{it} \times A} \times 100\%$$

where $\mathrm{GSSR}_{it}$is the grain self-sufficiency rate for the i-province in the t-year. G is the grain output and P is the number of permanent residents. A is an empirical coefficient, which is equal to 400 (Cui and Shoemaker, 2018).

3. Results

3.1. Key issues facing China's food security

(1) Who will farm in the future?

With the advancement of rapid urbanization, non-agricultural employment, aging and feminization of rural labor in China have become increasingly prominent (Chen et al., 2011; De Brauw et al., 2013; Huang and Jin, 2015). Since the implementation of the reform and opening-up policy in 1978, China's rural population has dropped significantly, and urban population has risen sharply. From 1978–2018, the rural population in China decreased from 790.47 million to 564.01 million, with an average annual decrease of 1.42%. In contrast, China's urban population increased from 172.45 million to 831.37 million, and the urbanization rate increased from 17.92% to 59.58% (Fig. 1). According to the latest data from China's seventh census, by the end of 2020, the rural population in China has further reduced to 509.79 million, the urban population has increased to 901.99 million, and the urbanization rate has risen to 63.89%.

Migrant workers (migrating from rural to urban areas for employment) are a manifestation of China's semi-urbanization. Migrant workers in China have increased from 225 million in 2008 to 286 million in 2020, with an average annual increase of 2% (NBS, 2021). Driven by the low efficiency of growing grain, many migrant workers would rather go out to work than grow grain at home, leading to the abandonment of large-scale arable land in rural China, especially in southern China. More importantly, China is currently facing multiple dilemmas such as a large-scale decline in the rural population, the aging of main body of farmers, the unwillingness of farmers to plant land, and young people's inability to cultivated land. Statistics show that between 1982 and 2019, China's rural aging rate increased from 4.56% to 15.8% (Fig. 2). The question of who will farm the land or who will feed China in the future deserves further reflection.

(2) Urban expansion took up large-scale high-quality arable land

Urban expansion has taken up a larger amount of high-quality arable land in China. Between 1978 and 2018, China's cultivated land area has been increasing and decreasing alternately, and the decreasing speed has been slowing down gradually. Although the amount of cultivated land in China has maintained a dynamic balance as a whole, the quality of cultivated land has not been guaranteed. Cultivated land occupied by urbanization is the main driving force for the reduction of cultivated land (Liu et al., 2018; Zhou et al., 2021). From 1981–2018, the urban built-up area of China has increased from 743,800 ha to 4613,600 ha, with an increase of 6.2 times (NBS, 2019). Statistics show that the area of cultivated land occupied by China's construction purposes increased from 83,800 ha in 1990 to 252,500 ha in 2017, with an average annual growth of 417 ha (MNR, 2018). The proportion of cultivated land occupied by construction in the area of cultivated land lost in China increased from 24.0% in 1990 to 82.5% in 2017 (Zhou et al., 2021).

From the perspective of growth rate (slope), from 1978 to 2018, the cultivated land area in Qinghai, Beijing, Shanghai, Hebei, and Guangdong showed a rapid decrease trend, while that in Heilongjiang, Yunnan, Inner Mongolia, Guizhou, Xinjiang and Jilin provinces showed a rapid increase trend (Fig. 3). Between 1978 and 2018, the cultivated land area declined in the eastern coastal areas, while that increased in the northeast, Southwest Yunnan Guizhou Plateau, Inner Mongolia Plateau and Xinjiang basin. The increase of cultivated land area in Northeast China (Jilin, Heilongjiang and Liaoning) and Inner Mongolia was due to the reclamation of marginal land under the background of climate warming, while the increase of cultivated land area in Southwest China was caused by deforestation. The decrease of cultivated land area in eastern coastal areas was mainly due to the expansion of built-up areas.

(3) China's grain production center shifted northward

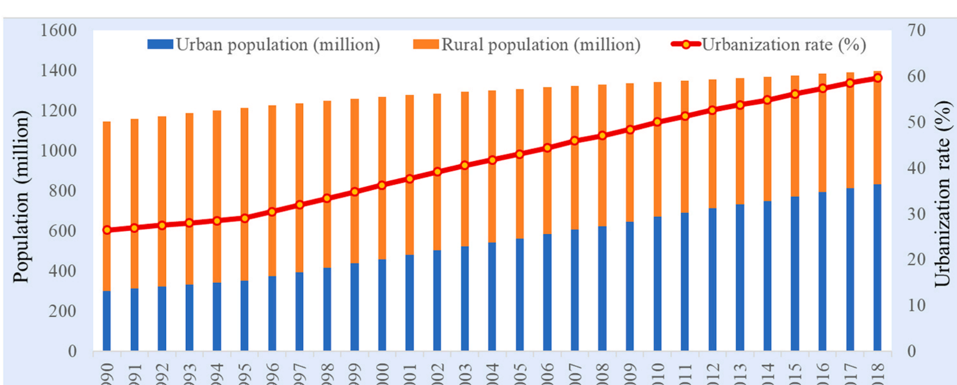

Fig. 1. Rural-urban population in China between 1990 and 2018. (Notes: Data are available from China Statistical Yearbook 1991–2019).

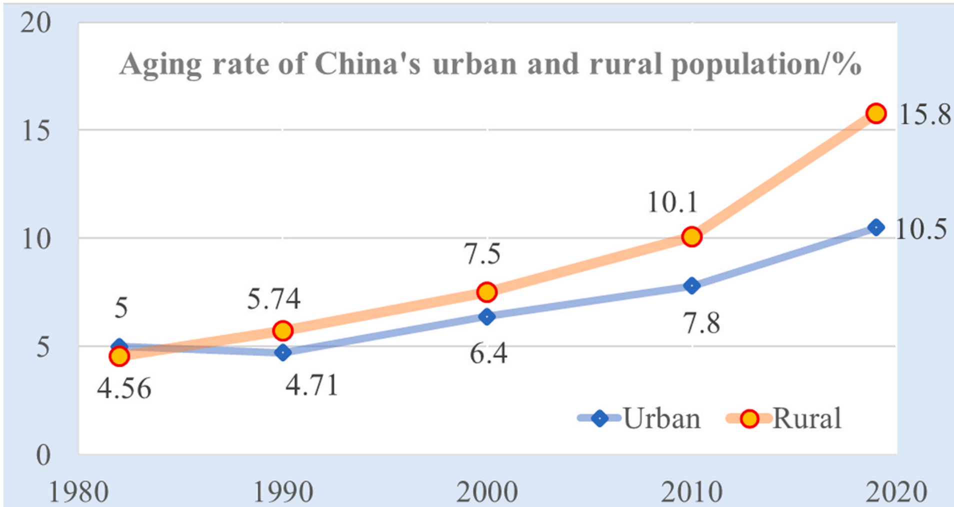

Fig. 2. Aging of China's urban and rural population between 1982 and 2019. (Notes: The data on urban and rural aging rates in 1982, 1990, 2000, and 2010 are from previous population censuses. The data for 2019 comes from the latest China Development Report 2020 issued by the China Development Foundation, Wei and Du, 2020).

Over the past 40 years, China's total grain production doubled, from 300 billion kg in 1978 650 billion kg in 2018. China's per capita food consumption increased from 316.6 kg in 1978 to 472.38 kg in 2018, which is far higher than the international food security standard of 400 kg per capita (NBS, 2019). Spatially, the grain production of most provinces in China increased over time, while that of only 6 provinces in 31 provinces (Zhejiang, Guangdong, Fujian, Sichuan, Beijing and Shanghai) decreased (Fig. 4). The grain output of Zhejiang Province showed the most obvious decline trend, with an average annual decline rate of 0.29 million kg, followed by Guangdong and Sichuan. The substantial reduction in grain output in the southeastern coastal area was related to the decrease in arable land and planting area, as well as the decline in the rural population in the area. The decline in grain output in Sichuan Province was mainly due to the substantial decline in the rural population, especially the employment of the primary industry. On the contrary, the provinces with the most obvious growth of grain production included Heilongjiang, Henan, Inner Mongolia, Jilin, Shandong, Hebei, and Anhui, among which the annual growth rate of Heilongjiang and Henan was more than one billion kg. In 1978, the grain production of Heilongjiang Province and Jilin Province was 150 billion kg and 190 billion kg, reached 751 billion kg and 665 billion kg by 2018, respectively. The grain output of Inner Mongolia, Jilin and Shandong increased at the rate of 690,000, 690,000 and 600,000 kg per year, respectively, and compared with 1978, the grain production of these three provinces increased by 19.7, 3.4 and 2.4 times by 2018.

In the context of climate warming, China's arable land area decreased in the south and increased in the north over the past four decades. Favorable climatic conditions have promoted the northward expansion of crop planting boundary in the north, and the country's grain production center has shifted northward, exacerbating the water shortage in the north (Liu et al., 2018, 2021). Over the past four decades, China's grain production pattern has undergone tremendous changes. The proportion of grain output in the 16 northern provinces of China in the total output of the country rose from 44.61% in 1978 to 51.64% in 1993, and further reached 64.70% in 2018 (Table 1). The three traditional major grain production areas in China were the Yangtze River Basin, the North China Plain, and the Northeast China. Historically, China's grain supply has always been higher in the south than in the north, forming a traditional pattern of "grain in the south being transported to the north" (*Nanliang Beiyun*). However, since 1978, urban expansion has occupied a large amount of cultivated land area, especially in the southeast coastal areas, resulting in the reduction of cultivated land area and grain production in the south. Since 1993, the grain output of northern China has exceeded its southern region for the first time, forming a pattern that the grain supply of norther China is more than that of the south. These results indicate that China' grain circulation pattern have been changed, from the traditional pattern of "grain in the south being transported to the north" (*Nanliang Beiyun*) to the present pattern of "grain in the north being transported to the south" (*Beiliang Nanyun*) (Xu et al., 2013). Therefore, China is currently facing the dilemma of the North Grain South Transportation (*Beiliang Nanyun*) and the South-to-North Water Transfer (*Nanshui Beidiao*). The eco-environment in northern China is fragile, and the shift of the grain production center to the north would exacerbate the already tense situation of water resources and the degradation of the ecosystem in northern China. The spatial mismatch of grain production and water and land resources will definitely affect the sustainability of China's grain production. Importantly, climate change is cyclical. In the future, the climate may become colder and the suitable grain growing areas in northern China will be narrowed, which would put more pressure on food security.

(4) Crop planting structure adjustment promoted the increase in food production

The adjustment of the main grain crop planting structure was also one of the driving forces for the continuous increase in China's grain output. Over the past 40 years, the increase in China's grain output was mainly due to the increase in corn output. From 1978–2018, China's grain output has increased from 304.76 billion kg to 657.89 billion kg, of which the proportion of rice output decreased from 44.93% to 32.24%, but the proportion of corn increased from 18.36% to 39.09%, and the proportions of wheat and soybeans remained at 20% and 2.5%, respectively (Fig. 5). The increase in corn output has made an important contribution to the increase in China's grain output. Between 1990 and 2018, China's corn planting area accounted for the proportion of grain crop planting area increased from 27.1% to 36.0%. The planting area of wheat has declined, and the planting area of rice has remained basically unchanged. Previous studies have also shown that from 2004 to 2014, the contribution rates of sown area, yield, and planting structure to China's grain output increase were 36.65%, 48.27%, and 15.08%, respectively (Yan et al., 2016).

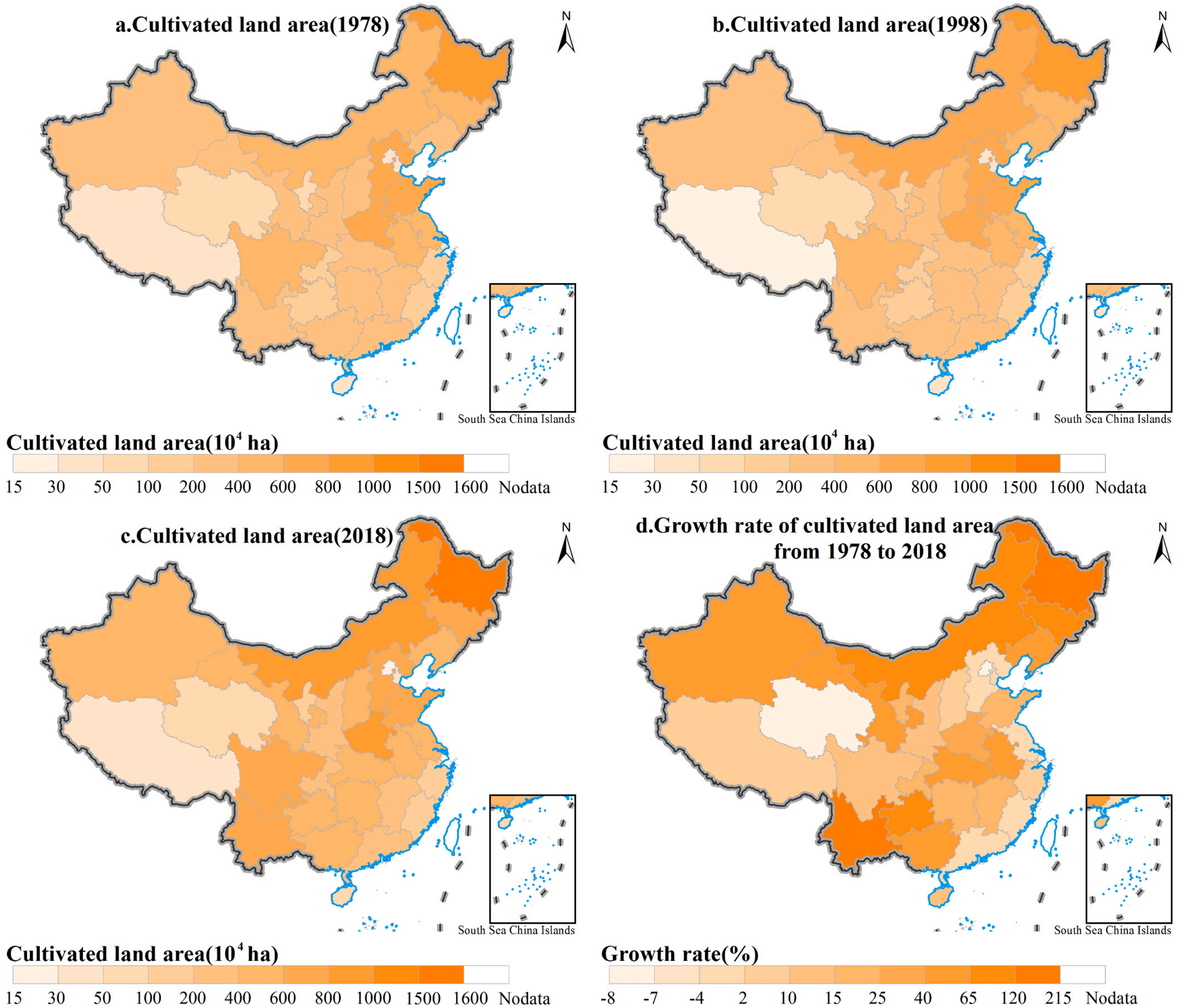

Fig. 3. Cultivated land area in China between 1978 and 2018.

(5) Coupling coordination degree (CCD) of population, land and grain (PLG) system decreased over time

The CCD of China's PLG system declined over time and varied across provinces. Of the 31 provinces in China, the CCD of PLG system in 20 provinces showed a downward trend. In 1978, the PLG's CCD were uncoordinated in 12 of 31 provinces in China, among which Beijing, Tianjin, Shanghai, Hainan, Ningxia, Qinghai and Tibet were seriously unbalanced (Fig. 6a). By 1988, the number of provinces with uncoordinated PLG system increased to 14 provinces, among which the CCD of Beijing, Tianjin, Shanghai, Hainan, Ningxia, Qinghai and Tibet were still extremely uncoordinated, and Shaanxi and Chongqing transformed from a basic coordination to a slightly incoordination (Fig. 6b). By 1998, the PLG system' coupling in 13 provinces across the country was in an uncoordinated state. The PLG system coupling in Inner Mongolia changed from a mild incoordination in 1988 to a basic coordination. Seven provinces including Beijing, Tianjin, Shanghai, Hainan, Ningxia, Qinghai and Tibet were still in a serious uncoordinated (Fig. 6c). From 1998–2008, with the rapid progress of urbanization in China, large-scale urban expansion in the eastern coastal areas occupied arable land, which led to a significant decline in the CCD of PLG system in the region, especially in Shanghai, Zhejiang, Beijing, Jiangsu, Guangdong, Fujian and Hubei provinces. By 2008, the PLG system in Beijing, Tianjin, Shanghai, Hainan, Ningxia, Tibet and Qinghai provinces was still serious uncoordinated, and that in Zhejiang, Fujian, Gansu, Chongqing, Xinjiang and Shanxi provinces was slight uncoordinated, while that in Henan, Heilongjiang, Shandong and Sichuan provinces was highly coordinated (Fig. 6d). By 2018, the number of provinces with coordination of PLG system increased to 16 provinces (Fig. 6e). Between 2008 and 2018, the PLG system in Guangdong, Guizhou, Shanxi and Shaanxi provinces changed from a basic coordination to a slight incoordination.

From the perspective of change trend, the cultivated land area in the eastern region decreased on a large scale due to rapid urbanization over the past four decades, and the growth trend of grain production decreased to varying degrees, leading to the decline of PLG system's CCD in eastern China. In the northeast and northwest of China, under the background of climate warming, large-scale marginal land reclamation has led to an increase in cultivated area and a northward expansion of the planting boundary, which led to an increase in PLG system's CCD in these areas. Interesting, Yunnan's rural population has decreased by a small amount over the past four decades, and the cultivated land area and grain output have been increasing slowly, resulting

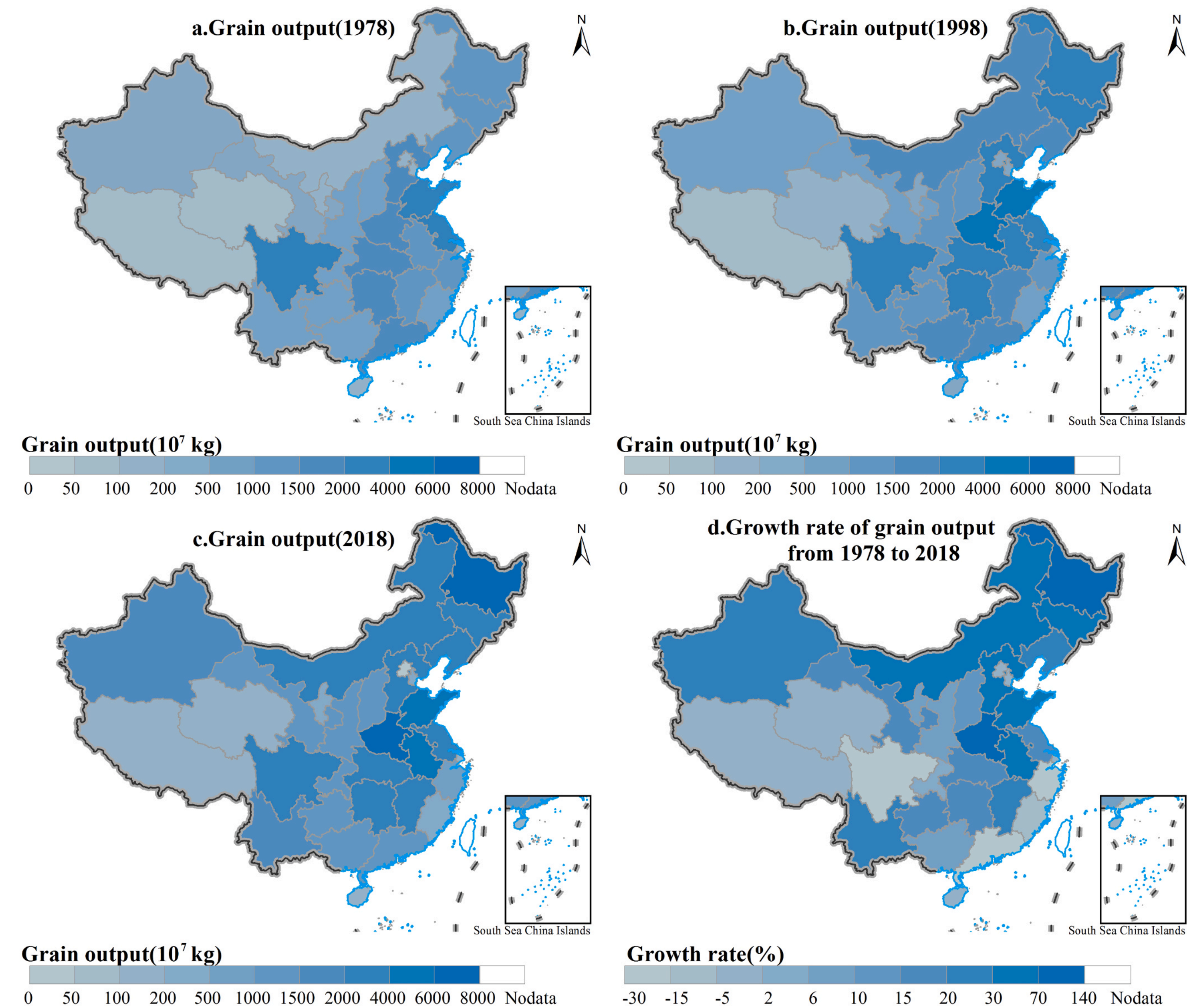

Fig. 4. China's grain output between 1978 and 2018.

in a rapid increase in the PLG system's CCD (Fig. 6f).

3.2. Influencing factors of grain output

Table 2 provides estimates for the impact of capital, land, labor and other factors on grain output for the entire sample (China) and for the four regions (eastern, central, western and northeast regions of China).[2] As the fixed effect models are the preferred models, our main interpretations focused only on these models. Most of the estimated coefficients were statistically significant at the 5% level or lower. The input of labor, technology, land and chemical fertilizer positively affected China's grain output, whereas the increase of non-grain crop area negatively affected grain output. The elasticities of grain output to the total power of agricultural machinery (POWER), the number of employees in primary industry (LABOR), the application amount of chemical fertilizer (FER) and cultivated area (ARABLE) were 0.24, 0.48, 0.08 and 0.35, respectively. Keeping other variables unchanged, a 1% increase in the total power of agricultural machinery increased grain production by 0.24% in China. A 1% increase in the number of employees in primary industry increased China's grain production by 0.48%. A 1% increase in cultivated land increased China's grain production by 0.35%. For every 1% increase in the proportion of sown area of non-food crops, China's grain output decreased by 1.37%. The results demonstrate that the increase of cultivated land area, the input of agricultural labor force, chemical fertilizer and the level of agricultural mechanization were conducive to the increase of China's grain output.

Regionally, the effects of labor, land, fertilizer and technology input on grain production were basically the same as that of the whole country, but the degree of impact varied across the regions. The increase of the total power input of agricultural machinery and labor force increased the grain output of four regions, and the increase of fertilizer use increased the grain output of the eastern, central and western regions, but the impact on the increase of grain output in northeast region

[2] According to the classification standard of the National Bureau of Statistics of China, the eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan; the central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan; the western region includes Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang, and the northeast China includes Liaoning, Jilin and Heilongjiang (http://www.stats.gov.cn/ztjc/zthd/sjtjr/dejtjkfr/tjkp/201106/t20110613_71947.htm).

Table 1
Food production and cultivated land between the south and north China from 1978 to 2018.[11]

Year	Food production				Cultivated land			
	South China		North China		South China		North China	
	Yield (MT)	Proportion (%)	Yield (MT)	Proportion (%)	Area (million ha)	Proportion (%)	Area (million ha)	Proportion (%)
1978	173.96	55.39	140.10	44.61	35.26	35.56	63.89	64.44
1979	190.77	55.77	151.30	44.23	35.21	35.42	64.20	64.58
1980	186.95	56.64	143.12	43.36	35.19	35.45	64.07	64.55
1981	188.81	56.35	146.26	43.65	34.96	35.36	63.91	64.64
1982	211.94	58.15	152.56	41.85	34.87	35.43	63.56	64.57
1983	219.60	55.10	178.98	44.90	34.78	35.41	63.43	64.59
1984	229.65	54.78	189.55	45.22	34.25	35.15	63.20	64.85
1985	213.59	54.79	176.22	45.21	34.17	35.26	62.74	64.74
1986	218.13	54.14	184.81	45.86	34.41	35.51	62.49	64.49
1987	221.68	53.27	194.43	46.73	34.30	35.50	62.30	64.50
1988	213.21	52.82	190.45	47.18	33.77	35.28	61.97	64.72
1989	226.38	54.16	191.62	45.84	33.76	35.29	61.90	64.71
1990	233.36	51.05	223.74	48.95	33.76	35.29	61.92	64.71
1991	232.05	51.98	214.40	48.02	33.72	35.25	61.94	64.75
1992	232.40	51.28	220.77	48.72	33.49	35.10	61.93	64.90
1993	225.86	48.36	241.16	51.64	33.22	34.93	61.88	65.07
1994	226.29	49.58	230.16	50.42	33.04	34.78	61.96	65.22
1995	237.82	49.74	240.34	50.26	32.96	34.70	62.01	65.30
1996	246.74	47.79	269.51	52.21	46.01	39.21	71.34	60.79
1997	241.04	48.78	253.14	51.22	33.58	33.69	66.09	66.31
1998	235.62	48.77	247.50	51.23	33.48	33.65	66.00	66.35
1999	240.51	47.31	267.88	52.69	43.99	37.05	74.74	62.95
2000	226.46	49.00	235.71	51.00	45.18	37.72	74.60	62.28
2001	213.65	47.20	238.99	52.80	44.97	37.68	74.37	62.32
2002	207.67	45.44	249.39	54.56	44.32	37.25	74.66	62.75
2003	198.04	45.98	232.65	54.02	43.30	37.17	73.19	62.83
2004	209.35	44.59	260.12	55.41	43.70	37.30	73.45	62.70
2005	212.58	43.92	271.44	56.08	42.79	36.23	75.32	63.77
2006	211.07	42.43	286.41	57.57	43.54	36.62	75.38	63.38
2007	210.16	41.90	291.44	58.10	44.36	37.01	75.49	62.99
2008	215.96	40.85	312.75	59.15	44.35	37.06	75.30	62.94
2009	221.55	41.74	309.27	58.26	46.12	35.29	84.57	64.71
2010	219.27	40.12	327.21	59.88	46.07	35.29	84.45	64.71
2011	223.07	39.05	348.15	60.95	46.04	35.29	84.41	64.71
2012	229.15	38.87	360.43	61.13	46.03	34.78	86.31	65.22
2013	229.93	38.20	372.01	61.80	46.03	34.78	86.31	65.22
2014	234.51	38.63	372.51	61.37	48.71	36.09	86.27	63.91
2015	237.63	38.24	383.81	61.76	48.67	36.07	86.26	63.93
2016	235.20	38.17	381.05	61.83	48.57	36.00	86.35	64.00
2017	233.98	35.36	427.63	64.64	48.53	35.98	86.35	64.02
2018	232.26	35.30	425.63	64.70	48.52	35.98	86.33	64.02

Data sources: NBS, 2019.

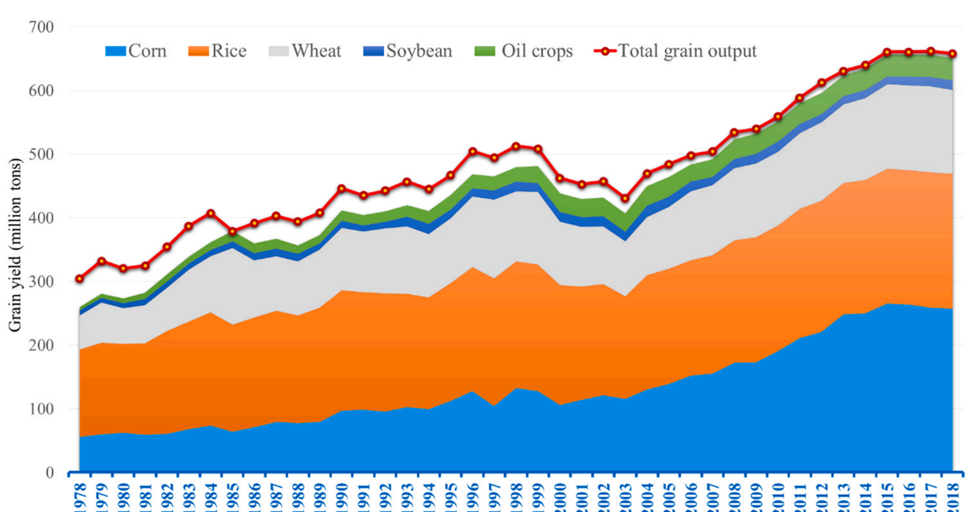

Fig. 5. China's main grain output between 1978 and 2018. (Notes: data are from China Statistical Yearbook 1979–2019).

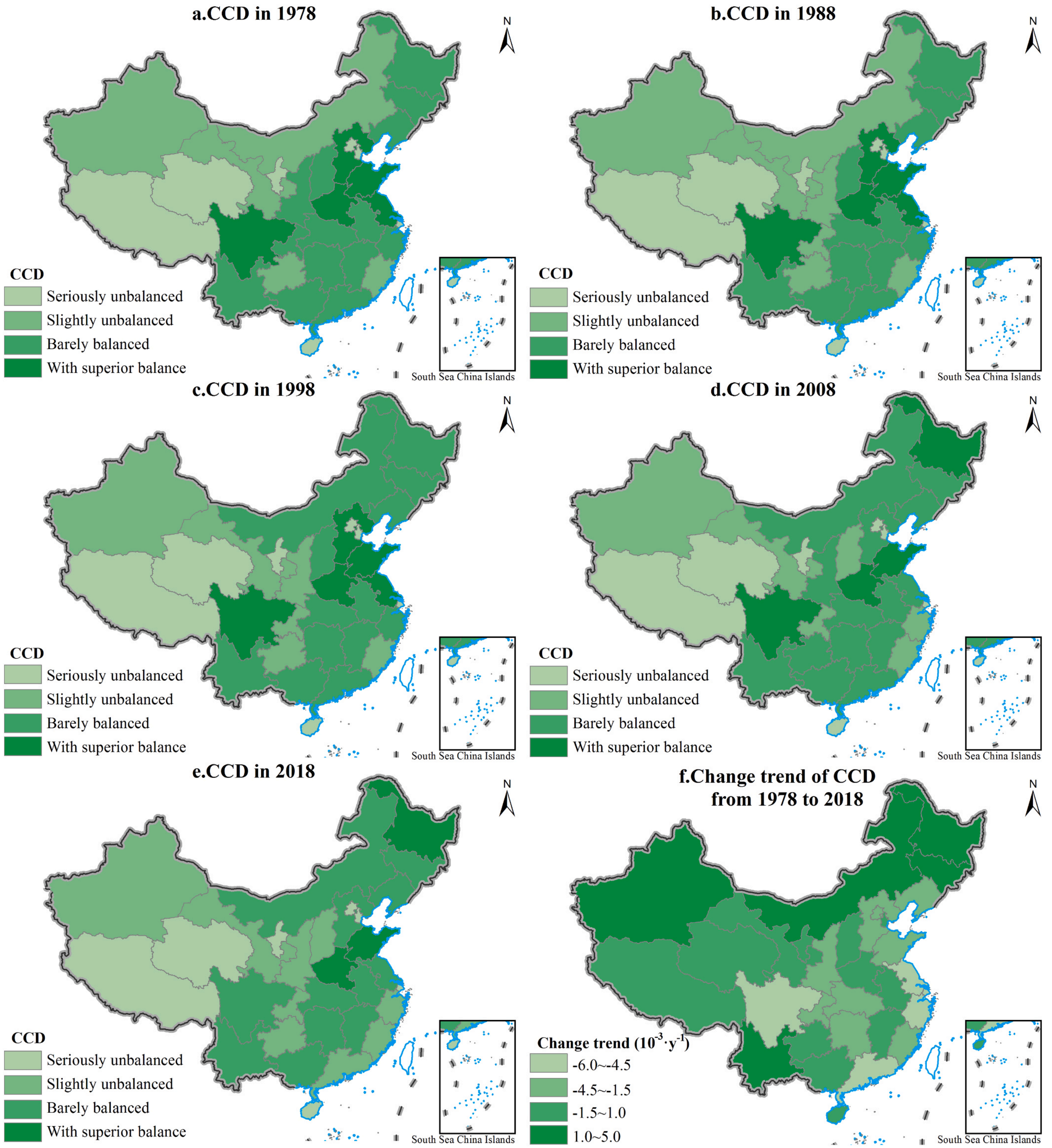

Fig. 6. Coupling coordination degree (CCD) of China's PLG system between 1978 and 2018.

was not significant. In addition, the increase of cultivated land area significantly increased the grain production in the eastern, western and northeast regions, but it was not conducive to the increase of grain production in the central region. The increase of planting area of non-grain crops has led to the decrease of grain yield in four regions. The main factors influencing the increase of grain yield in different regions were different. The impact of total power of agricultural machinery on grain production in Northeast China was higher than that in western, central and eastern China. The impact of the increase of rural labor force on the western region was more obvious, the use of chemical fertilizer was more obvious in the eastern region, and the increase of cultivated

[1] In this study, the grain yield and cultivated land area of southern and northern China from 1978 to 2018 and their proportion in the whole country were calculated. Generally, northern China includes Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Anhui, Shandong, Henan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang; southern China includes Shanghai, Jiangsu, Zhejiang, Fujian, Jiangxi, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan and Tibet.

Table 2
Estimated results for grain output for China and its four regions.

Variable	The entirety of China		Eastern region		Central region	
	OLS	Fixed effect	OLS	Fixed effect	OLS	Fixed effect
ln(POWER)	0.242[c]	0.243[c]	0.208[c]	0.214[c]	0.337[c]	0.242[c]
	-0.011	-0.011	-0.016	-0.016	-0.019	-0.016
ln(LABOR)	0.482[c]	0.475[c]	0.208[c]	0.188[c]	0.831[c]	0.028
	-0.027	-0.03	-0.042	-0.043	-0.03	-0.078
ln(FER)	0.080[c]	0.083[c]	0.147[c]	0.148[c]	-0.032[b]	0.142[c]
	-0.011	-0.011	-0.023	-0.024	-0.015	-0.017
PANC	-1.340[c]	-1.373[c]	-2.545[c]	-2.609[c]	-0.152	-0.960[c]
	-0.078	-0.079	-0.14	-0.141	-0.151	-0.169
ln(ARABLE)	0.347[c]	0.351[c]	0.485[c]	0.447[c]	-0.429[c]	-0.310[c]
	-0.03	-0.032	-0.063	-0.069	-0.058	-0.087
Constant	-0.593[c]	-0.588[b]	0.548	0.930[b]	2.877[c]	7.791[c]
	-0.221	-0.243	-0.394	-0.455	-0.308	-0.993
R-squared		0.646		0.651		0.786
Obs.	1266	1266	409	409	246	246
Variable	Western region		Northeast China			
	OLS	Fixed effect	OLS	Fixed effect		
ln(POWER)	0.236[c]	0.236[c]	0.295[c]	0.299[c]		
	-0.024	-0.024	-0.04	-0.068		
ln(LABOR)	0.667[c]	0.669[c]	0.273[b]	0.582[c]		
	-0.05	-0.057	-0.111	-0.124		
ln(FER)	0.052[c]	0.057[c]	0.158[c]	0.046		
	-0.018	-0.019	-0.026	-0.033		
PANC	-0.463[c]	-0.477[c]	-3.036[c]	-1.903[c]		
	-0.143	-0.146	-0.37	-0.415		
ln(ARABLE)	0.231[c]	0.228[c]	0.258[c]	0.386b		
	-0.04	-0.041	-0.045	-0.165		
Constant	-1.138[c]	-1.138[c]	1.216[a]	-1.541		
	-0.366	-0.407	-0.676	-1.468		
R-squared		0.689		0.873		
Obs.	488	488	123	123		

Notes: POWER is total power of agricultural machinery; LABOR is number of employees in primary industry; FER is application amount of chemical fertilizer; PANC is planting area of non-grain crops; ARABLE is cultivated area. OLS is ordinary least square regression and Fixed effect is fixed effect model, respectively. Standard errors in parentheses.

[a] Indicate statistical significance at the 10% level.

[b] Indicate statistical significance at the 5% level.

[c] Indicate statistical significance at the 1% level.

land area was more obvious in the eastern region. The effect of the adjustment of agricultural planting structure on the reduction of grain production in the western region was significantly higher than that in the other three regions.

4. Discussion

Over the past four decades, the increase of grain production in China was the result of climate warming, marginal land reclamation, technological progress and main grain crop planting structure adjustment. Climate warming has recognized as one of the driving forces for increased food production in China's mid- and high-latitude regions (Yang et al., 2010; Gao and Liu, 2011; Qin et al., 2015; Liu et al., 2019a, 2021). This is because climate warming has led to the reclamation of marginal land in northern China and the expansion of the planting border to the north, creating favorable conditions for the adjustment of a one-crop annual cropping system to a two-crop annual cropping system in north China (Yang et al., 2010; Qin et al., 2015; Liu et al., 2019a). Scientific and technological progress, government policy support, increased investment and favorable climate conditions have created favorable conditions for China's sustained grain production. The contribution rate of scientific and technological advances to China's agricultural production has increased from 20% in 1949 to 60% in 2020 (Xinhua Agency, 2020). To some extent, advances in science and technology have concealed China's potential food security crisis. The use of seeds, chemical fertilizers, pesticides and agricultural film has promoted the increase in grain production, but it has also brought serious soil pollution problems (Guo et al., 2020).

Although food production continues to rise, China's food security is facing potential crises that are affected by factors such as climate volatility, extreme weather events, tightening water and land resource constraints, frequent natural disasters, rapid urban expansion, large-scale food waste and international trade instability (Lam et al., 2013; Ghose, 2014; Dalin et al., 2015; Lu et al., 2015; He et al., 2017; Wang et al., 2017; Cui and Shoemaker, 2018; Liu et al., 2019b; Xue et al., 2021). The Chinese government has always regarded high food output and high self-sufficiency as the most important indicators for measuring food security (Yu et al., 2019). However, in recent years, the so-called "three highs" (high outputs, high stocks and high imports) have emerged in China's food supply and sales, and trade, which means that while domestic food output continues to increase, food imports and government-held stocks have also increased sharply, raising concerns about China's food security (Yu et al., 2019; Zhong and Zhu, 2017; Xin and Li, 2018). International cereal prices are much lower than those prevailing in the domestic markets, which leads to an increase in China's food imports. Statistics show that from 1990 to 2018, although China's food output increased from 446.24 billion kg to 657.89 billion kg, while food imports increased from 13.69 billion kg to 115.55 billion kg. Soybean imports accounted for a major proportion of China's total food imports. If soybean is excluded, total food imports present an increasing trend while total food exports vary between years. Especially since 2010, soybean imports accounted for more than 50% of China's food imports. By the end of 2017, 95.53% of China's soybeans depended on imports (Fig. 7). China' soybean is highly dependent on foreign countries. In addition, the country's huge food stocks continue to impose severe pressures on its production and trade policies. Meanwhile, it also faces the double squeeze of the "high floor" of cost and the "ceiling" of price and subsidy as well as the constraint of the two "hoops" of land and

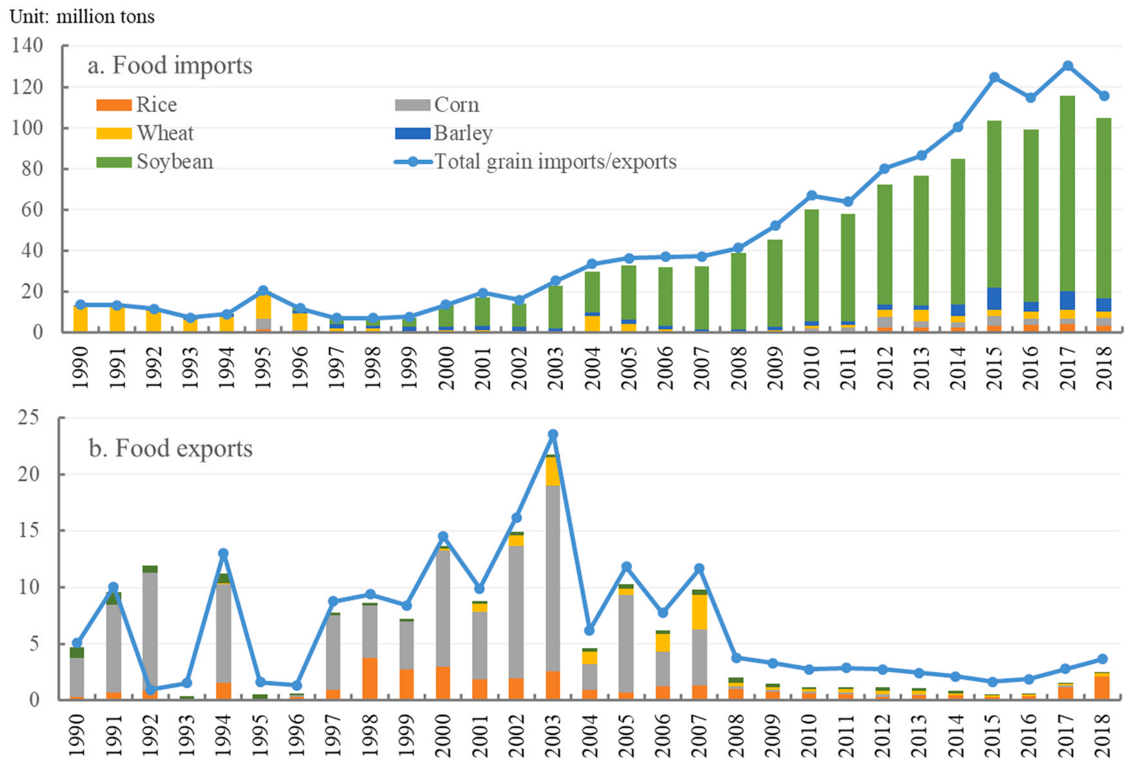

Fig. 7. China's total food imports (a) and exports (b) between 1990 and 2018.

water resource shortage and soil pollution (He, 2015). Fluctuations in international food prices have an important impact on China's food security (Ghose, 2014). China's annual food waste accounts for 27% of its food production, also threatening the country's food security (Liu et al., 2013b; Xue et al., 2021).

The spatial mismatch between China's water and land resources and food production patterns affects food security. Over the past 20 years, with the rapid progress of urbanization, a large area of cultivated land in the south China has been occupied, while affected by climate warming, a large-scale marginal land has been reclaimed in the North (Liu et al., 2014a), thus forming a pattern of food production in northern China exceeding that in the south. Without considering the food trade, the food

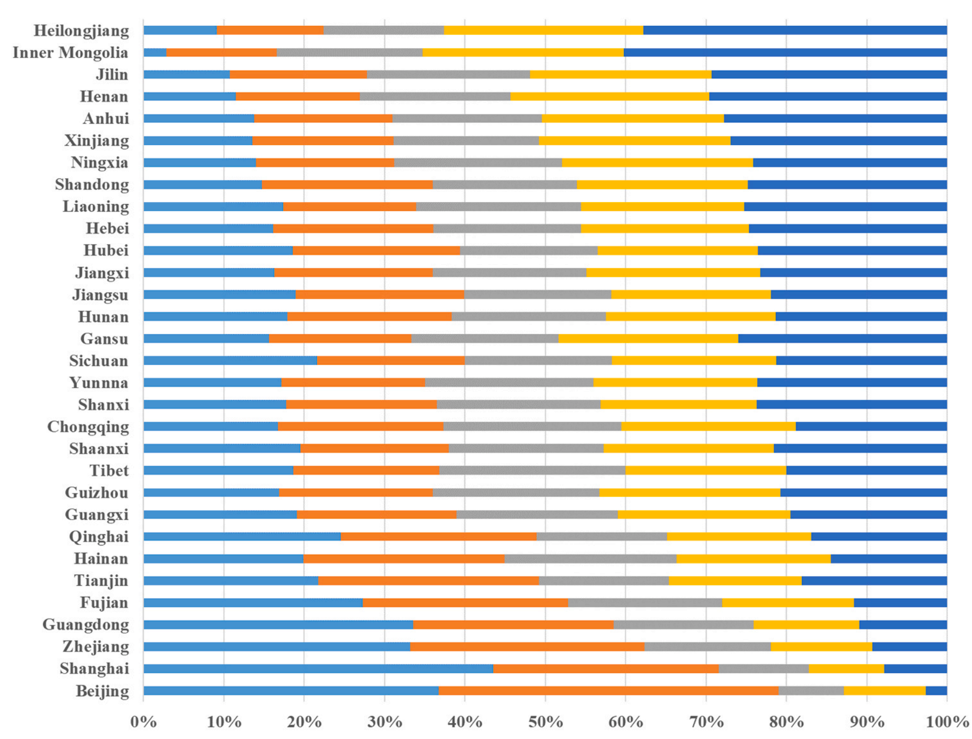

Fig. 8. Food self-sufficiency rate of 31 provinces in China from 1978 to 2018.

self-sufficiency rate is estimated based on the per capita food consumption of 400 kg. Our results show that the top five provinces with the highest food self-sufficiency rate in China in 2018 were Heilongjiang (795.85%), Inner Mongolia (560.90%), Jilin (537.38%), Henan (276.89%) and Anhui (253.47%), and the provinces with insufficient food self-sufficiency rates were Beijing (6.33%), Shanghai (17.1%), Zhejiang (41.77%), Guangdong (42.08%), Fujian (50.61%), Tianjin (53.77%), Hainan (63%), Qinghai (68.39%) (Fig. 8). Obviously, the self-sufficiency rate of food was relatively high in the plain areas of Northeast China, North China and the middle and lower reaches of the Yangtze River, and that was seriously insufficient in Beijing, Shanghai, Tianjin and the southeast coastal areas. The imbalance of food supply and demand has become increasingly serious in southern China and economic development areas such as Beijing, Tianjin and Shanghai.

China's food production center moved northward, which has a profound food security crisis. Agriculture faces great challenges to ensure global food security by increasing yields while reducing environmental costs (Foley et al., 2011; Tilman et al., 2011). The proportion of grain output in China's 13 major grain producing areas (including Heilongjiang, Jilin, Liaoning, Inner Mongolia, Hebei, Shandong, Henan, Hubei, Jiangxi, Hunan, Sichuan, Jiangsu and Anhui) in the country's total has dropped from 90.78% in 1978 to 88.37% in 2018. Since 2000, the number of provinces for net transfer of food has decreased from 13 provinces to 6 provinces. Among the 11 provinces with balanced production and marketing, the self-sufficiency rate of grain in 9 provinces has dropped from an average of 97% in 2003 to 58% in 2020 (Du, 2020). Constrained by resources and the environment, China's main grain producing areas are under increasing pressure to increase production. Due to climate warming, rapid urbanization and agronomic management, the centroid of Chinese rice production shifted northeastward over the past decades. The gravity center of food production has kept northward moving since 1990 and moved from the Kaifeng county of Henan province in 1990 to southern Weixian of Hebei province in 2014 (Wang et al., 2018). The North China Plain has to overexploit the groundwater to sustain agricultural production, which has resulted in the area becoming the largest funnel area in the world (Kang and Eltahir, 2018).

Food security is greatly affected by global environmental change (Yu et al., 2012). Food security in China is undoubtedly under threat as farmland shrinking, soil pollution, land degradation and water shortage, climate change and excessive reliance on fertilizers and pesticides (Liu et al., 2013b). The process of ecologicalization, urbanization and non-grainization is threatening China's food security (Chen, 2007; Lu et al., 2015; Kuang et al., 2021). In the past 20 years, the country has carried out large-scale industrialization and urbanization construction. The cultivated land area in the south China has declined sharply, and urban expansion has occupied large-scale high-quality farmlands (Kuang et al., 2016, 2021; Liu et al., 2018; Zhou et al., 2020b; Kuang, 2020). Rapid urban expansion has converted highly productive cultivated land at the urban-rural fringe to non-agricultural uses at enormous rates (Tan et al., 2005). In addition, the increase in labor costs and land costs has promoted the rapid increase in the cost of food production in China. The per mu cost of grain production rose from 150 yuan in 1990–1100 yuan in 2018, with an increase of 7.3 times (Du, 2020). The cost of grain planting and production has increased, but the value of grain output has been declining due to the impact of international grain prices, and the comparative benefit of growing grain has declined, frustrating farmers' enthusiasm for growing grain and increasing the risk of farmland abandonment. Urban expansion has put pressure on China's food security by reducing cropland net primary productivity (He et al., 2017). Furthermore, agriculture is practiced in highly fragile land in China, causing serious soil and water erosions and ecosystem degradation (Bennett, 2008). More importantly, Chinese farmers have not really got rid of the traditional agricultural business model. Of course, China's agricultural high-yield has the credit of modern science and technology, but it depends more on chemical fertilizers and pesticides. Due to the overuse of fertilizers and unreasonable land use patterns, over 40% of the cultivated land was degraded, and 16.1% of soil and 19.4% of farmland was contaminated (Zhao et al., 2015). Rapid cultivated conversion, freshwater deficits, soil contamination and land degradation have also led to a decline in China's food production potential (Lam et al., 2013).

Agriculture is one of the most vulnerable industries to climate change, especially in developing countries. Previous studies have shown that precipitation was the main reason for China's food production fluctuations, and the impact of temperature on food production was mainly reflected in high latitude and high-altitude areas (Yang et al., 2010). Climate warming has an obvious promoting effect on the increase of total food production in Northeast China, while it has a certain inhibiting effect on the increase of total food production in North China, northwest and southwest China (Hu et al., 2019). From 1961–2010, climate change had a significant adverse impact on the climatic potential productivity of maize in China (Guo et al., 2014).

With the advancement of urbanization and the growing emphasis on ecological civilization construction, the CCD of China's PLG system will be further reduced. China will inevitably face the dilemma between ecological construction and cultivated land protection. Over the past four decades, China's PLG system's CCD in the eastern coastal areas and most western regions have experienced a rapid decline. Although the ecological environment in the western region has been greatly improved in the past two decades and the vegetation coverage has been significantly improved due to the implementation of the GFG program, the area of arable land has decreased greatly and the potential for food production has declined (Chen et al., 2019; Piao et al., 2020; Wang et al., 2020; Shi et al., 2020). It is predicted that in a long period of time in the future, China's population will be further reduced and rural population will also be greatly reduced (Chen et al., 2020). In the next 30 years, the urbanization of China's eastern coastal areas will inevitably occupy a lot of cultivated land (Feng et al., 2020). Affected by climate change and urbanization, food output in the eastern region will further decline (Ye and Van Ranst, 2009; Ye et al., 2013; Yuneng et al., 2020). All these factors will lead to a further decline in the PLG system's CDC in the eastern region, and the contradiction between human and land relations will intensify. In the context of increasing importance of ecological civilization construction, the western region not only undertakes the task of ecological restoration, but also faces the double predicament of protecting cultivated land and ensuring food security.

Public health emergencies and extreme weather disasters can also affect food security. In 2020, novel coronavirus disease (COVID-19) pandemic has caused global economic slowdown and disruption of the food supply chain, and global food prices have been rising continuously and forced more than 150 million people in the world to fall into extreme poverty and over 7 million people died of hunger, exacerbating global hunger and food insecurity (UN, 2020; FAO, 2020). COVID-19 pandemic has posed a huge challenge for many developing countries around the world to achieve the sustainable development goal of eradicating hunger by 2030 as scheduled (Udmale et al., 2020; Health, 2020). COVID-19 has posed a threat to global food security by affecting labor shortages, crop cultivation, agricultural and food market chaos, and insufficient food supplies (Laborde et al., 2020; Pereira and Oliveira, 2020). In addition, global extreme weather events are becoming more frequent, posing a serious threat to food security (Schmidhuber and Tubiello, 2007; Wheeler and Von Braun, 2013; Wei et al., 2017; IPCC, 2021). For example, the extremely heavy rain that occurred in Henan Province, China starting on July 20, 2021, triggered floods and affected 14.814 million people in 150 counties and caused the direct economic losses more than 133.7 billion yuan in the province, and 1.08 million ha of crops were affected and 0.34 million ha of crops have no harvest (China Net, 2021).

5. Conclusions and policy implications

This study systematically discussed the potential threats to China's food security and identified the key factors affecting China's food production. Results show that over the past 40 years, China's rural population decreased on a large scale, and cultivated area decreased in the south and increased in the north, and food output shown a rising trend. The increase of China's food production is the result of the total power input of labor force, chemical fertilizer, agricultural machinery and the increase of cultivated area. Although China's food production has maintained a steady upward trend, there are hidden regional, structural, and technical crises. After years of high grain yields, China's food supply and demand have undergone some phased changes, structural contradictions have become increasingly prominent, and tendencies problems have begun to emerge. Potential factors affecting China's food security include the non-agriculture use of arable land, the aging and weakening of farmers, the spatial mismatch of water and land resources, the periodicity and instability of climate change, and the unbalanced spatial coupling of PLG system. Between 1978 and 2018, the CCD of China's PLG system has shown a rapid decline, especially in areas such as the eastern coast of China and the Sichuan Basin. Regionally, the PLG system coupling has been in a coordinated state in Northeast China for a long time, while has been in a serious uncoordinated state in Beijing, Tianjin, Shanghai, Hainan, Ningxia, Qinghai and Tibet. The PLG system coupling in the eastern coastal areas of China gradually decreased, and the human-natural relationship became increasingly tense. Over the past two decades, China' food circulation pattern has changed from the traditional pattern of "food in the south being transported to the north" to the present pattern of "food in the north being transported to the south". The centroid of food production has moved northwards and crossed the Yellow River, which has created new pressures on the already scare water resources in north China and affected the sustainability of the agricultural system. Larger-scale loss of cultivated land, the migration of agricultural population to cities, the abandonment and non-grainization and non-agriculturalization of farmland, and the decline in food production potential have threatened China's food security.

COVID-19 pandemic has caused some countries such as Vietnam, Russia, Kazakhstan and India to suspend or restrict food exports, and sounded the alarm for China's food security. Ensuring food security requires holding the rice bowl firmly in your own hands so that you have food in your hands and you are not panicking. Six measures should be taken to ensure China's food security. First, we must adhere to the strictest farmland protection system, attach equal importance to the quantity protection and quality improvement of farmland, strictly adhere to the red line of 1.8 billion acres of farmland, and insist on curbing the "non-agriculturalization" and "non-grainization" of cultivated land. It is necessary to vigorously promote the black soil protection project in Northeast China, and formulate a strategy for continuous grain production under the background of the aging of the main body of grain production. Second, under the premise of ensuring that the total amount of food production does not decrease, it should optimize the structure of agricultural production and increase the efficiency of agricultural production. It is necessary to speed up the construction of functional areas for grain production and protection zones for the production of major agricultural products in accordance with the principle of comparative advantage to optimize the distribution of grain production areas. Third, this country should promote the cultivation of fine varieties, promote the comprehensive land consolidation of order-type, integrate land consolidation with development and utilization, promote the integration of land consolidation and utilization. The comprehensive consolidation of land in empty and waste villages and the construction of high-standard farmland are also urgent. Fourth, it must accelerate the development of modern agriculture and digital agriculture in China, and improve the quality of agricultural products and agricultural competitiveness. The development of modern agriculture needs to change the traditional mode of high input, high pollution and low output. China should make full use of unmanned aerial vehicle (UAV), big data, Internet of things, blockchain technology to monitor crop cultivation, management, transportation, sales and other links to ensure that the agricultural development process can be traced and restored, and develop modern, organic and ecological agriculture to guarantee the quality and safety of agricultural products. Fifth, it is urgent to increase food subsidies and implement competitive food purchase prices to mobilize farmers' enthusiasm for food cultivation, cultivate new-type professional farmers, reduce the cost of food production, and avoid large-scale occupation of arable land by urbanization. Sixth, it must attach great importance to China's land protection and the north-south regional balance of food production, improve the comprehensive agricultural production capacity in the south, and realize the cultivated land protection and stable food production in the north. There is an urgent need to accelerate the establishment mechanisms of agricultural ecological compensation and cultivated land protection, and to make a trade-off between cultivated land protection and urbanization construction. Finally, differentiated countermeasures should be also adopted to ensure China's food security. The eastern coastal areas in China should implement intensive and economical land use policies and take advantage of the country's rural revitalization strategy to consolidate the hollow villages. Southwest China should further strengthen the Karst rock desertification control, improve the ecological compensation mechanism, increase food subsidies, reduce cultivated land abandonment, and coordinate the promotion of cultivated land protection and food production. Northwest China should strengthen the comprehensive management of desertified land. Northeast China should strengthen research on the adaptation and response of agricultural production systems to climate change, and alleviate the negative impact of extreme climate change on agricultural production.

CRediT authorship contribution statement

Yansui Liu: Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition, Supervision. **Yang Zhou**: Methodology, Software, Data processing, Formal analysis, Writing – original draft, Writing – review & editing.

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Conflict of Interest Statement

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. The work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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