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Analysis of the spatial mismatch of grain production and farmland resources in China based on the potential crop rotation system

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ABSTRACT

At present, China's grain production pattern runs counter to the distribution patterns of farmland resources and water-heat conditions. It is urgently important to conduct research on the spatial matching of grain production and farmland resources. Based on the Potential Crop Rotation data, with regards to the situations of irrigation and rain feeding, this paper builds a measuring model of potential farmland, and separately measures the spatial matching index of grain yield with actual and potential farmland resources, thus revealing China's grain production pattern. The results indicate that serious spatial mismatch exists between grain production and farmland resources in China. Take the potential crop rotation system into consideration, the spatial mismatch of grain yield and potential farmland resources has been aggravated by the grain production barycenter's shift to the north China, with low Crop Rotation Index. The function-promoting regions of grain production in China are going through two evolution patterns of "northward and southward expansion" and "westward movement and northward expansion," respectively. Inefficient use of farmland mainly occurs in the fragile ecological environments, such as the farming-pastoral ecotone of Northern China, the northwest area of Xinjiang and the southwest karst landform areas. The inefficient use of and the decreasing amount of available farmland have become the main causes of the decline in grain production. The problems facing Chinese agriculture caused by the spatial mismatch include the imbalance in regional structures, ecological risks, agricultural production risks, and the risk of food price. In order to cope with these problems, this paper provides some advices on protecting farmland acreage, expanding farmland potential, ensuring the safety of water resources, and extending the industrial grain chain. Our paper additionally proposes policy reforms and innovations designed to ensure the implementation of the above measures, so as to commonly defuse China's food security crisis.

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1. Introduction

Food security is a fundamental problem related to the sustainable development of a country's social economy and national security. The food security situation in China is being confronted with many challenges (Anderson and Strutt, 2014; Enenkel et al., 2015; Fan and Brzeska, 2014). Since the 1990s, the urbanization and industrialization of China has entered the acceleration stage, which features the disordered expansion of urban construction land and the occupation of a large amount of high-quality farmland (Ding, 2007), as well as the over-use of agricultural water resources (Brown et al., 2005; Thompson and Prokopy, 2009; Yue et al., 2013). A large number of people from rural areas now swarm into cities. This migration of huge numbers of people gradually intensifies the decreased use of farmlands for agricultural purposes, while increasing its non-agricultural use (Gu et al., 2007; Li et al., 2014; Long et al., 2012, 2016; Su et al., 2015; Seto et al., 2000). Soil pollution, land degradation and water pollution all intensify the food security problem (Liu et al., 2015; Lu et al., 2015; Qing et al., 2015; Xu et al., 2014). Continuous population growth and changes in residents' consumption patterns lead to a greatly increasing demand

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for food (Dorward, 2013; Unnevehr and Hoffmann, 2015; Mitchell, 2008). Food security has in fact been a cause of great concern for a very long time (Ferranti, 2016; Pinstrup-Andersen, 2009; Smyth et al., 2015; Zhou and Turvey, 2014).

With the continuous development of regional economies, obvious changes have occurred in terms of the grain production and supply-demand patterns in China (Lu, 1997; Deng et al., 2013). Some research has shown that the barycenter of grain production presents a trend of "northward and middle-part forward movement" (Liu and Zhai, 2009). Statistics also indicate grain circulation pattern changes, from the traditional pattern of "grain in the south being transported to the north" to the present pattern of "grain in the north being transported to the south" (Xu et al., 2013a; Liu et al., 2009). Driven by factors such as per capita farmland acreage, grain yield per unit area, and economic benefits (Xu et al., 2013b), grain production will in the future be concentrated in the northern and western regions. These areas boast a low proportion of non-agricultural income, great potential for improving grain yield per unit area and high economic benefits (Deng et al., 2013). The spatial pattern of per capita grain growth also indicate a new prospect of "low growth in the middle region and high growth in the western region" (National Bureau of Statistics of China, 2010). The imbalanced spatial distribution of grain production is causing year-by-year increases in grain trade volume between the main producing areas and the main selling areas. This imbalance will have a profound impact on regional grain policy and interprovincial grain trade (Wu, 2000).

The present pattern of grain production in China commonly results from multiple factors. Grain production is not only affected by certain specific natural factors, such as the location of farmland (He et al., 2013; Song et al., 2015; Xu and Zhu, 2015), crop rotation systems (Cornish et al., 2015a,b; Rigolot et al., 2016), climate change (Bandara and Cai, 2014; Cheeseman, 2016; Rutten et al., 2014; Ye et al., 2014), and the condition of available water resources (Chen et al., 2013a; Jiang, 2015; Xu et al., 2005), but also affected by a number of external factors, including chemical fertilizer use (Smith and Siciliano, 2015; Zhao et al., 2016) and modernized agricultural conditions (Wang and Zhou, 2013; Su et al., 2014a). The farmland resources in China are confronted with the dual challenges of quantity and quality. As such, the sharp decrease of available farmland (Chien, 2015) and intensified land degradation (Jiang et al., 2015) directly threaten China's grain yield. Global climate change is also leading to a northward shifting of the crop rotation system boundary, to an increase in the Multiple Cropping Index (Ye et al., 2015) and to more frequent occurrences of climate-related damage (Marvin et al., 2013). Combined, these factors bring new opportunities and challenges to grain production in China. The spatial imbalance of water resources causes the water resource occupation per farmland acre in South China to be eight times greater than that in North China. The implementation of a "South-to-North Water Diversion" Project, at least to a certain extent, relieves the pressure caused by the shortage of water resources in northern regions. However, the spatial mismatch of water resources and grain production cannot be neglected forever (Dong et al., 2011; Li et al., 2015). Water pollution (Lu et al., 2015) and the massive increase in non-agricultural water usage (Davijani et al., 2016) further restrict any potential improvement in overall grain production capabilities. The progress of agricultural technology is a "double-edged sword", because while the use of chemical fertilizers and pesticides increases the grain yield, meanwhile, those same fertilizers and pesticides also cause problems such as agricultural non-point source pollution (Smith and Siciliano, 2015), soil crust (Shahgholi and Abuali, 2015) and other issues. Without doubt, the spatial shifting of both grain production and farmland resource barycenters is magnifying the crisis that grain production faces in terms of water, soil, and ecology.

Therefore, the need to conduct research on the spatial matching degree of grain production and farmland resources is urgent. Previous studies have mostly focused on analyzing the correlation between grain production and actual farmland areas (Long and Zou, 2010; Robinson and Carson, 2015; Liu et al., 2014, 2009). These studies neglected the changes in grain sowing areas caused by the different crop rotation systems. The hydrothermal resources in the southern region are very rich, and the production potential per unit area of farmland is far greater than that of the northern area. The spatial mismatch of the grain production and farmland resources caused by the northward shifting of the grain production barycenter is causing a serious waste of resources. Based on the Potential Crop Rotation data which examines the situations of irrigation and rain feeding, this paper builds a model of measuring potential farmland. Separately, we measure the spatial matching index of grain yield against actual and potential farmland resources. Through analyzing and comparing the two index-measuring results, we can reveal the main grain-producing areas, as well as the most inefficient farmland utilization areas, and we further analyze the function degradation areas and potential areas of grain production. We also use this data to judge whether or not the spatial pattern of grain production is in accord with the distribution rules of potential farmland, and provide corresponding suggestions to ensure China's food security.

2. Materials and methods

2.1. Data source and processing

The data relating to grain yield, irrigated areas (*IA*) and total cultivated area (*TCA*) of 2,347 counties in China, in 1990, 2000 and 2010, was mainly extracted from "*China Statistical Yearbook for Regional Economy*" and "*China County Statistical Yearbook*". The data pertaining to 100 m gridded farmland in 1990, 2000 and 2010, was provided by National Data Sharing Infrastructure of Earth System Science (www2.geodata.cn). The data pertaining to 10 × 10-kilometer grids of Potential Crop Rotation Index (PCRI) for the irrigated and rain-fed scenarios in 1990, 2000 and 2010, was provided by Global Change Research Data Publisher & Repository (www.geodoi.ac.cn). It was estimated with GAEZ-model developed by FAO and IIASA, based on DEM data, soil data, meteorological data and arable land. The PCRI includes single, 1.5 times, double and triple crop rotation systems.

The PCRI was resized from 10 kilometer to 100 m grids, in order to calculate the potential farmland combined with actual farmland. Eventually, the actual farmland and potential farmland were calculated at county level.

2.2. Methods

Potential farmland area denotes the natural potential area of physical farmland. For example, the potential farmland was two times the actual farmland in a double crop system. Therefore, potential farmland is given as (Liu et al., 2014):

$$y_p = y \times PCRI_i \times i + y \times PCRI_r \times (1 - i) \tag{1}$$

$$i = \frac{IA}{TCA} \tag{2}$$

where, y_p is the area of potential farmland, y is the area of actual farmland, $PCRI_i$ and $PCRI_r$ is the PCRI under irrigated and rain-fed scenarios, respectively; i is the ratio of irrigated area (IA) to the total cultivated area (TCA).

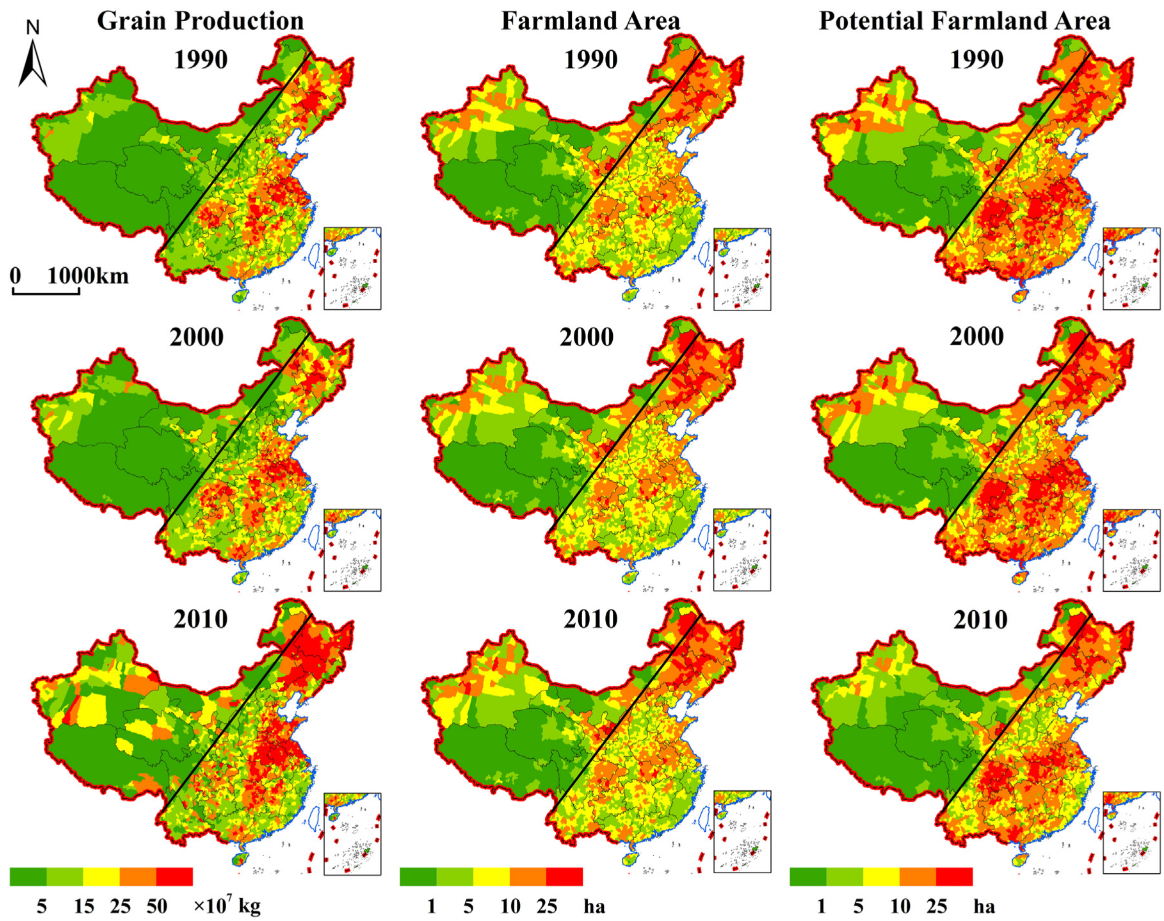

Fig. 1. The spatio-temporal pattern of grain production, farmland and potential farmland. The inclined line is called "HU Line".

The model of gravity center fitting is used to reveal the displacement rule of grain yield, farmland and potential farmland and is calculated as follows:

$$x_j = \sum_{i=1}^{n} \left(T_{ij} \times x_i\right) / \sum_{i=1}^{n} T_{ij}$$
$$y_j = \sum_{i=1}^{n} \left(T_{ij} \times y_i\right) / \sum_{i=1}^{n} T_{ij} \quad (3)$$

where, n is the number of counties, $P_j(x_j y_j)$ represents the national barycentric coordinates of grain yield (farmland, potential farmland) in year j, $P_i(x_i y_i)$ stands for the barycentric coordinates of grain yield (farmland, potential farmland) of county i, and T_{ij} stands for the grain yield or area of farmland (potential farmland) of county i in year j.

Spatial mismatch refers to the imbalance between grain yield and farmland area, which is currently a hot topic in China. The spatial mismatch index of grain-to-farmland (SMIGF) is used to measure the spatial relationship of grain-to-farmland and is calculated as follows:

$$SMIGF\_A_i = \left(G_i / - F_i / \sum_{i=1}^{n} G_i \sum_{i=1}^{n} F_i\right) \times 100$$
$$SMIGF\_P_i = \left(G_i / - \mathrm{PF}_i / \sum_{i=1}^{n} G_i \sum_{i=1}^{n} \mathrm{PF}_i\right) \times 100 \quad (4)$$

$$\sum SMIGF\_A = \sum_{i}^{n} |SMIGF\_A_i| \quad \sum SMIGF\_P = \sum_{i}^{n} |SMIGF\_P_i| \quad (5)$$

$$\Delta SMIGF_i = SMIGF\_A_i - SMIGF\_P_i = (PF_i / \sum_{i=1}^{n} PF_i - F_i / \sum_{i=1}^{n} F_i) \times 100 \quad (6)$$

where, $SMIGF\_A_i$ represents the spatial balance between grain yield and actual farmland area. $SMIGF\_P_i$ is used to measure the spatial mismatch between grain yield and potential farmland area. G_i and F_i are the grain yield and farmland area of county i, respectively. $\sum SMIGF\_A$ ($\sum SMIGF\_P$) represents the degree of total spatial mismatch between grain yield and farmland area (potential farmland area) in China. Actually, $SMIGF\_A_i$ is the comparison between the location quotient of grain yield and that of the farmland area in county i. When the absolute value of $SMIGF\_A_i$ is less than a cretain value, there is a spatial match between grain production and farmland. When the absolute value of $SMIGF\_A_i$ is more than the value and the $SMIGF\_A_i$ is negative, there is a spatial mismatch between grain production and farmland. In addition, the location quotient of farmland area is larger than that of grain yield, which means the use of farmland in county i is inefficient. Conversely, when the absolute value of $SMIGF\_A_i$ is more than the value and the $SMIGF\_A_i$ is positive, the spatial mismatch still exists, but the location quotient of grain yield becomes larger than that of farmland, which in turn means that the farmland in county i is used efficiently. The same

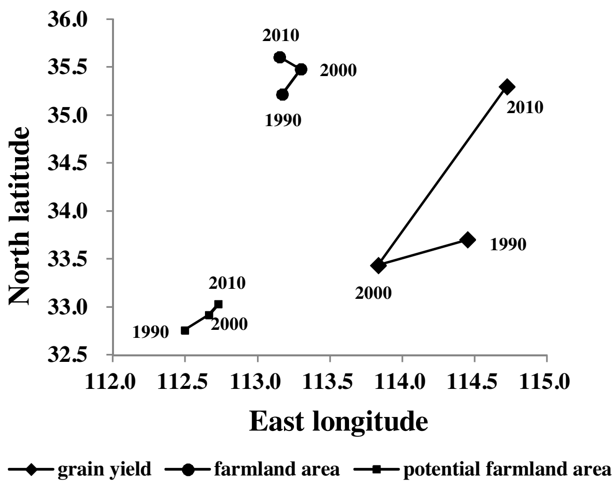

Fig. 2. The trajectory of the barycenter of grain yield, farmland area and potential farmland area.

is true for $SMIGF\_P_i$. $\sum SMIGF\_A$ ($\sum SMIGF\_P$) increases with the degree of spatial mismatch between grain production and farmland (potential farmland). $\Delta SMIGF_i$ is the variance between the $SMIGF\_A_i$ and $SMIGF\_P_i$, and is actually the difference between the location quotient of potential farmland and actually farmland. $\Delta SMIGF_i > 0$ implies the great potential of the farmland resources of county i, and vice versa.

The Gini coefficient can be used to detect the equilibrium between grain yield and farmland area, and it is specified as:

$$G = 1 - \sum [a \times (2b - c)] \tag{6}$$

where G is the Gini coefficient, a and c are the proportion of farmland area and grain yield of each county, respectively, and b is the cumulative proportion of the grain yield of each county. Usually, the Gini coefficient is between 0 and 1. If the farmland area and grain yield reach a greater degree of equilibrium, the Gini coefficient becomes smaller, and vice versa.

3. Results

3.1. The spatio-temporal pattern of grain production and farmland resources

The distribution of grain production and farmland resources in China are restricted by the "HU Line"[1]; (Fig. 1). Most of these areas with high grain yield and abundant farmland resources are concentrated in the southeast region of the "HU Line". The concentrating tendency for the spatial distribution of grain yield is becoming more and more obvious. The spatial distribution of the actually and potential farmland are, however, relatively stable. The Potential Crop Rotation Index (PCRI) in China is characterized by high level in southern and eastern regions and low level in northern and western regions. Thus, in southern and eastern China, potential farmland area is larger than actual farmland resources. When combined with the barycenter model (Fig. 2), we found the barycenters of grain yield, farmland area and potential farmland area all shifted to north China. The barycenter of grain yield presented a radical northward shifting. However, that of the farmland area and potential farmland area presented a slight northward shifting. In addition, the barycenter of potential farmland area located in the south of that of farmland area and grain yield. Therefore, it is necessary to discuss the issue of spatial mismatch between grain yield and potential farmland area.

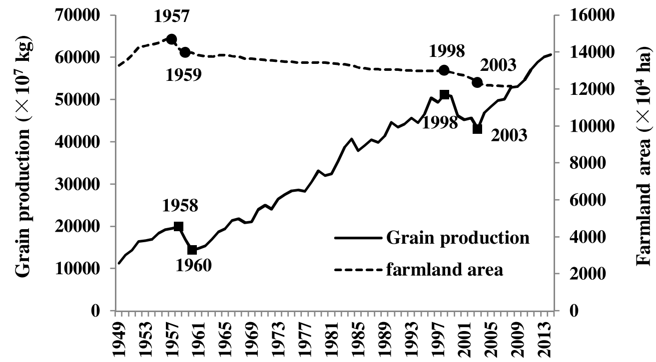

Fig. 3. The grain yield and farmland area of China since 1949.

Grain yield is not only affected by farmland area, but also affected by other factors. The changing rules relating to grain yield and farmland area are reviewed since the founding of the country (Fig. 3). At the beginning of the country, when the farmland areas were scarce, grain yield changed positively with the change of increased farmland areas. Since 1960, when farmland areas were relatively sufficient, the input of external factors (fertilizers, irrigation, new species, new technology, mechanization) increased the grain yield. At the beginning of the 21st centrury, the marginal benefits provided by these external factors with regard to the level of grain production began to decrease, so farmland area again became the main constraint to increasing the grain yield. However, due to the implementation of the "Grain for Green" policy in 1998, as well as the increasing phenomenon of rural-to-urban migration, a great number of farmers swarmed into the cities, and the instances of farmland being abandoned was staggering. The continuous sharp decrease in the use of farmland area caused a corresponding radical decrease in the grain yield. In 2003 the grain yield had decreased to 0.48 billion tons. In the same year, at the Third Plenary Session of the 16th CPC Central Committee, it was proposed to "carry out the strictest farmland protection policy to ensure the food security of the country". Since then, the rate of decrease in farmland area has decelerated, and the grain yield has continuously increased.

3.2. The Gini coefficient and the $\sum SMIGF$

This paper uses the Gini coefficient together with $\sum$SMIGF to measure the spatial matching degree of grain yield with farmland resources throughout the whole of China. The results of these two expressions possess similar changing characteristics (Fig. 4). During the period from 2000 to 2010, both the Gini coefficient and $\sum$SMIGF presented a trend of sharp increase, and the spatial mismatch between grain production and farmland resources became more serious. Through the comparison between $\sum$SMIGF_A and $\sum$SMIGF_P, we found that in the early periods covered by the study, $\sum$SMIGF_P was always less than $\sum$SMIGF_A. There was no doubt that, grain production was concentrated in the regions with good hydrothermal conditions, and the farmlands with multi-crop systems were used sufficiently. However, in 2010, $\sum$SMIGF_P overtook $\sum$SMIGF_A, and the spatial mismatch between potential farmland resources and grain production was higher than that between actual farmland resources and grain yield. It could be seen that, during this period, the inefficient use and even abandonment of farmland resources with multi-crop systems was very common.

[1] HU line, is a "geo-demographic demarcation line" discovered by Chinese population geographer HU Huanyong in 1935 (Hu, 1935). The imaginary Heihe (in Heilongjiang)-Tengchong (in Yunnan) Line divides the territory of China into two parts: northwest of the line covers 64% of the total area but only 4% of the population; however, southeast of the line covers 36% of the total area but 96% of the population (Long and Li, 2012).

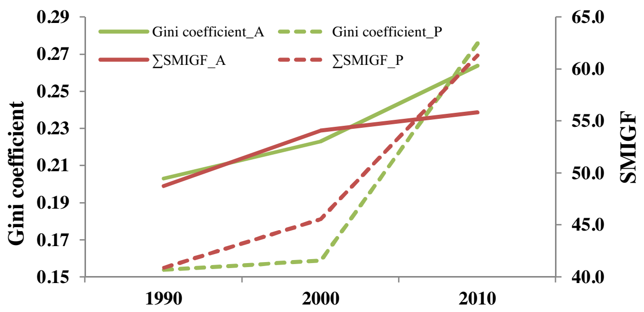

Fig. 4. The Gini coefficient and $\sum$SMIGF of grain production and farmland during 1990–2010.

3.3. *The spatio-temporal pattern of SMIGF_A*

Based on Jenks Natural Breaks Classification in ArcGIS software, the paper used −0.02 and 0.02 as the cutoff threshold values to determine efficient or inefficient uses of farmland. As shown in Fig. 5, the degree of the spatial matching of grain yield and farmland resources was going from bad to worse during this period. As seen from the regions with serious spatial mismatch, the regions with inefficient utilization of farmland was mainly distributed in the Greater Khingan Mountains, northern farming-grazing transitional zones and the northwest area of Xinjiang. In 2010, these regions extended to the southwest karst landform area. All of these areas are regions in China with the fragile ecological environments (Peng et al., 2011). In the highly efficient farmland utilization regions, or the main grain-producing areas, the spatial distributions showed greater differences. In 1990, the main grain-producing areas were mainly distributed over the Pearl River Delta region, Yangtze River Delta region and the middle reaches of the Yangtze River. In addition, the main grain-producing areas were also scattered in the Sichuan Basin, the Huanghuaihai Plain and northeastern China. In 2000, the barycenter of grain production began to shift to the Huanghuaihai Plain. The remediation of the saline-alkali lands contributed to the increase of grain yield per unit farmland area. The function of grain production in the Huanghuaihai district was strengthened. Meanwhile, due to the ample sunshine and rainfall of the Pearl River Delta region, the grain-producing potential of farmland resources in this area was further tapped, and the function of grain production was enhanced even further. Conversely, the grain-producing function of the middle and lower reaches of the Yangtze River was substantially weakened. Additionally the non-agricultural use and inefficient utilization of the farmland persisted, which caused the grain yield to sharply decline.

The decreasing scope of the grain yield was in fact larger than that of farmland areas. The northward shifting of the grain production barycenter began to take shape. In 2010, the pattern of "westward movement and northward expansion" for grain production came into full effect, and the grain-producing function in the Pearl River Delta region substantially deteriorated. In the middle and lower reaches of China's Yangtze River (known as "a land flowing with milk and honey"), the main grain-producing areas were greatly reduced, and the grain-producing function in the Zhejiang, Hubei and Sichuan Basin was weakened. On the contrary, the grain-producing function in the northeastern and northwestern China was greatly improved. Corresponding with global warming, the farming boundary in the northeastern China extended to the north, while the crop rotation system changed from a one-season pattern to a multi-season pattern (Gao and Liu, 2011). Driven by the economic development and the West Development Strategy of China, efforts were intensified to exploit the farmland in the western regions, and the inputs of agricultural technology and capital were increased rapidly, thus causing the grain yield and even the SMIGF_A to increase.

The dynamic changes in the SMIGF_A are, in essence, direct comparison between the relative changes in the Location Quotients of grain yield and farmland area in different years. The increase of the SMIGF_A indicates that the grain yield allows for a relative higher increase of Location Quotient than farmland area, which in turn shows the improvements in both farmland-utilization efficiency and grain-producing function. Conversely, the Location Quotient has, relatively speaking, reduced, which indicates serious extensive utilization of farmlands and a trend towards a weakening grain-producing function. Overall, the SMIGF_A during the period from 2000 to 2010 changed most radically. The changes in the spatio-temporal pattern during this period tallied with that during the period from 1990 to 2010.

Also during the period from 1990 to 2000, the efficiency of farmland-utilization was an important factor which affected the spatio-temporal pattern of the SMIGF_A. A pattern of southward and northward expansion from the Yangtze River valley emerged (Fig. 6).

(1) The regions with decreasing SMIGF_A were mainly situated on the plains in the middle and lower reaches of the Yangtze River, as well as in northeastern and western China. In the 1990s, the plains in the middle and lower reaches of the Yangtze River were the most rapidly urbanized regions in our country. These regions rapidly transformed from a grain-producing function to a function of socio-economic development. Under these circumstances, the move away from the agricultural and food-producing utilization of farmland was inevitable. Driven by both the decrease in farmland area and the increasingly inefficient use of farmland, the decline rate of the Location Quotient for grain yield far exceeded that of farmland area. Different from the decreases of both grain yield and farmland areas, however, the areas showing a decline of SMIGF_A in northeastern and western China also commonly showed an increase of farmland area and a decrease in grain yield. Land remediation and reclamation supplemented the farmland resources, but the increase in farmland area hardly offset the decrease in grain yield accelerated by the inefficient use of farmland. Together, these factors caused the SMIGF_A in these regions to decline. On this basis, the inefficient use of farmland is the main cause of the country's decreased grain yield.

(2) In the regions with an increasing SMIGF_A, the grain yield also commonly increased. In the southern, southwestern, western and northeastern China, both grain yield and farmland area increased simultaneously. The rate of increase of the Location Quotient for grain yield was higher than that for farmland, with the intensive level of the farmlands improved. However, in the Huanghuaihai Plain, the regions with increasing SMIGF_A commonly showed a trend of increasing grain yield and decreasing farmland area. As the region with highest density of population, industries and towns in northern China, in the urbanization process of Huanghuaihai Plain, the non-agricultural use of farmland was an indisputable fact. However, the Huanghuaihai district possesses a natural advantage in terms of grain production, with deep soil layers, fertile soil, ample sunlight and heat resources, and optimum levels of rain and heat over the growing period. There is a good mix and match between sunlight, heat, water and soil in this area. Additionally, the flat landscape makes larger-scale mechanized operations easier to achieve. Any negative effect of decreasing farmland area on grain yield can be reduced by improving the efficiency of farmland utilization, which will in turn help achieve the goal of increasing the region's grain yield.

During the period from 2000 to 2010, as the marginal benefits of external factors in the grain production process decreased successively, the farmland area again became the main constraint to

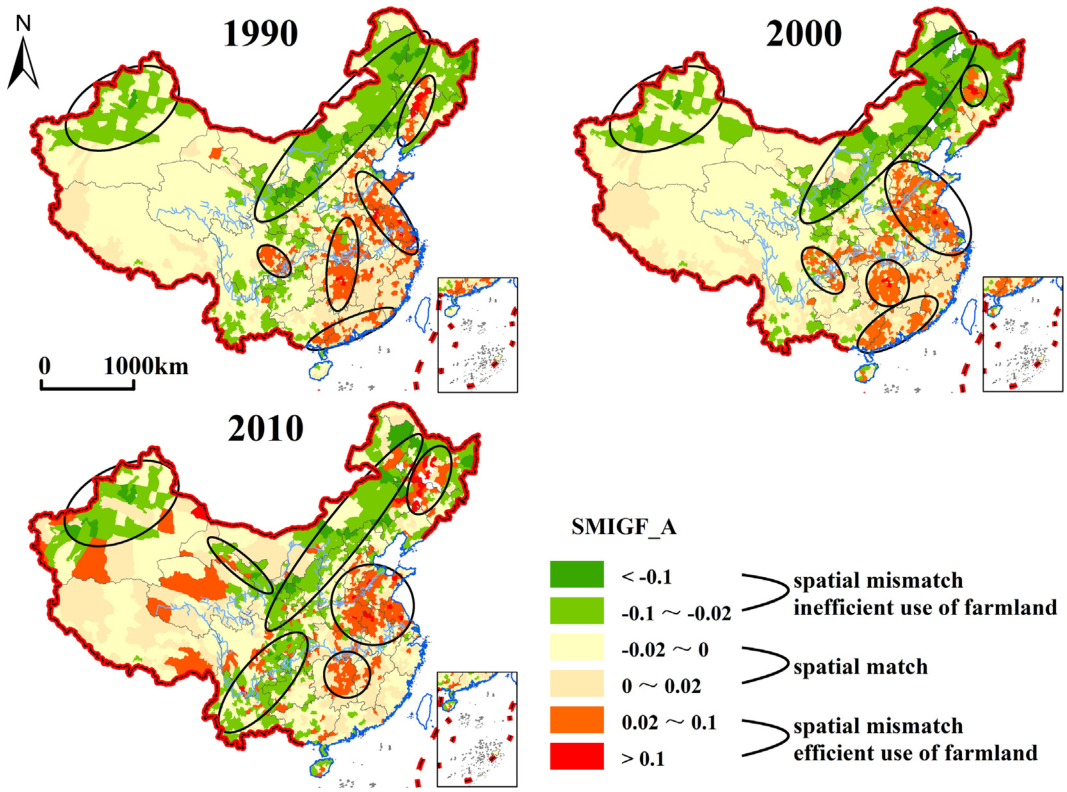

Fig. 5. The spatio-temporal pattern of SMIGF_A from 1990 to 2010.

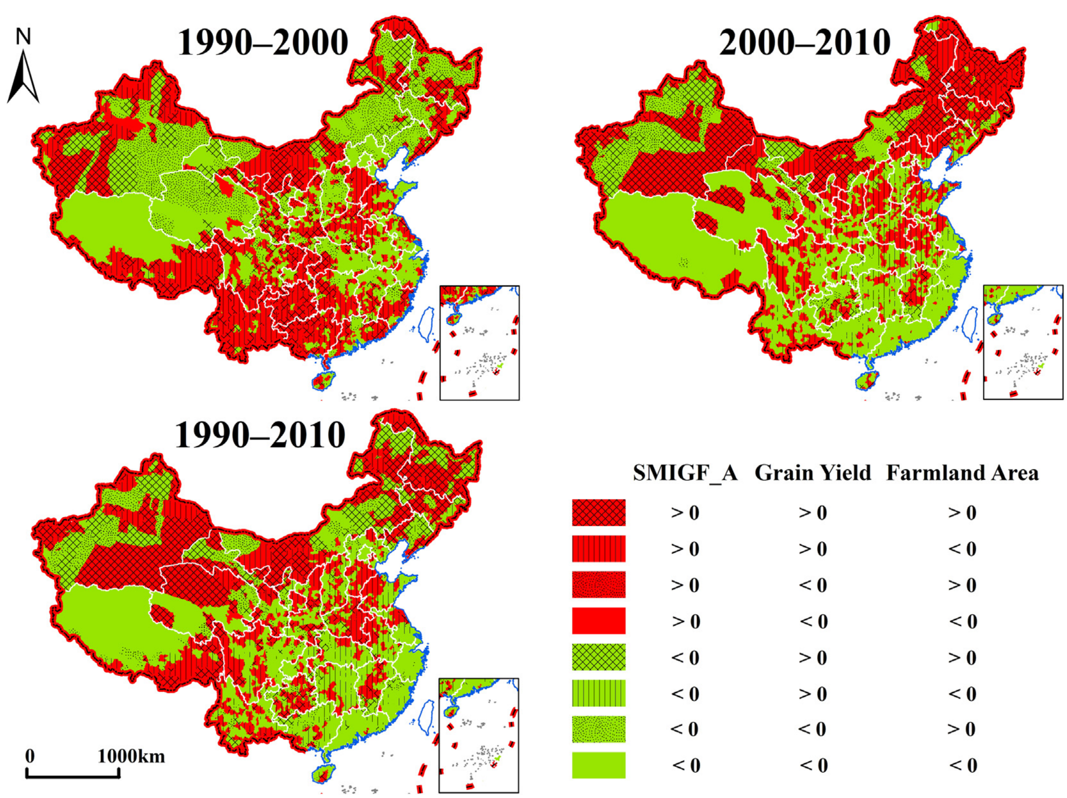

Fig. 6. The dynamic change of SMIGF_A, grain yield and farmland area.

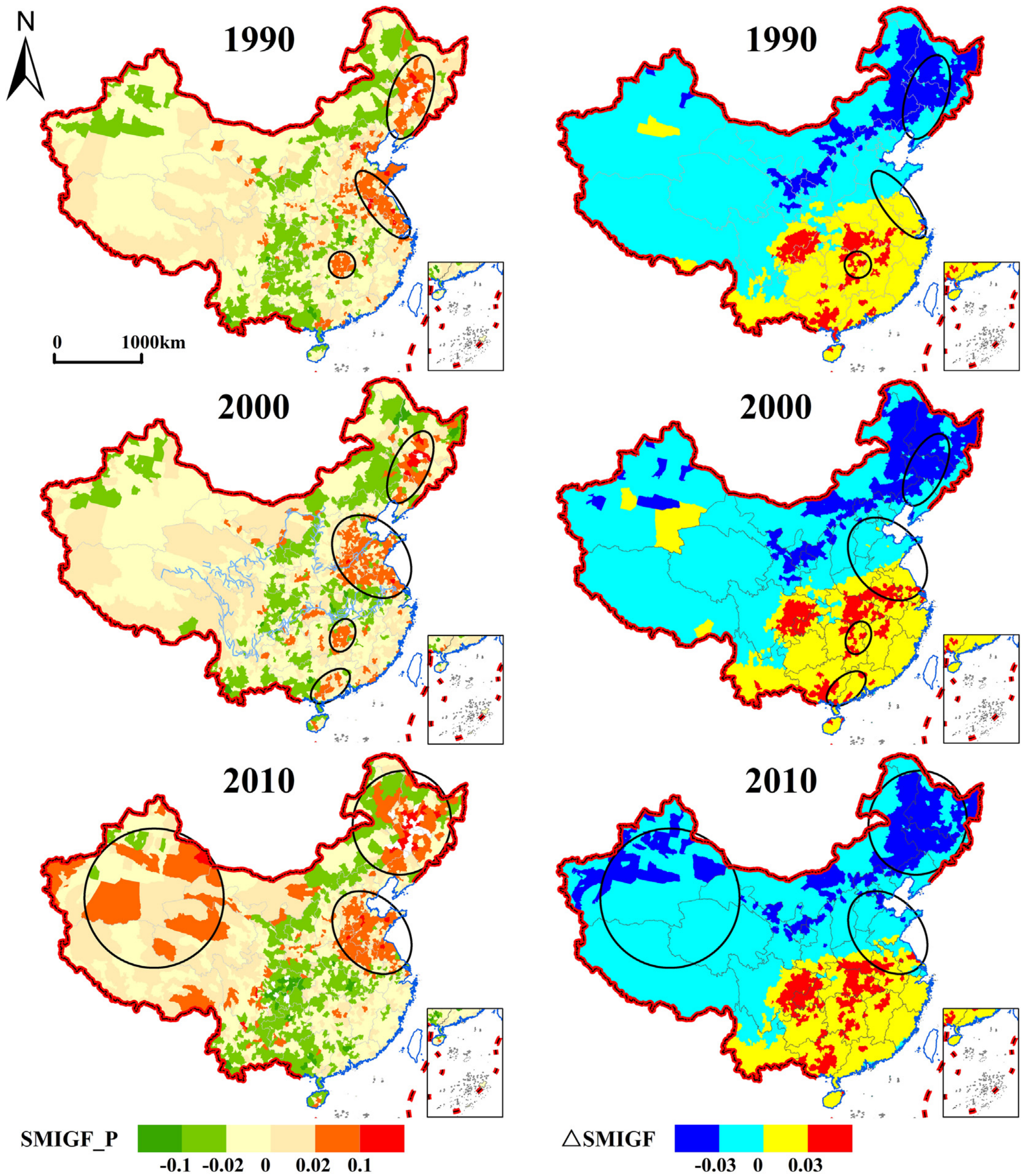

Fig. 7. The spatio-temporal pattern of SMIGF_P and △SMIGF during the period from 1990 to 2010.

increasing the grain yield. Both SMIGF_A and farmland showed a pattern of reducing in the south and increasing in the north (Fig. 6).

(1) The southern and eastern parts of China (Guangdong, Fujian, Zhejiang and the southern area of Jiangsu) presented a phenomenon of decreases in both farmland area and grain yield, leading to a SMIGF_A decrease. These regions' marketization level are very high, and the handicraft, business and electronic industries in many villages are very advanced. The farmers have a high level of consciousness in terms of starting their own businesses, so the regions almost naturally experienced a transformation from agricultural to non-agricultural industries. This transformation made the inefficient use of and even the abandonment of farmland inevitable.

(2) In most areas within the Yangtze River Valley, SMIGF_A decreased. At the same time, this decrease was accompanied by an increase in grain yield and a decrease in farmland area. Despite the increased grain yield, the Location Quotient for grain yield in this region still decreased, due to the larger and increasing amplitude of grain yield in the northeastern and western China. In addition, the decrease of the Location Quotient for grain yield was larger than that for farmland areas. The grain-producing function decreased.

(3) In the county areas between the Yangtze River Valley and the northern farming-grazing transitional zone, the SMIGF_A showed both increasing and decreasing patterns, while the farmland areas in this region presented a trend of general reduction. The areas with decreasing SMIGF_A tallied with the distribution of city groups.

(4) Large increases in both grain yield and farmland area were evident in three northeastern provinces of China, as well as in Inner-Mongolia and the northwestern region. As the efficiency of grain production improved, these areas became the main regions with newly-increased grain yield. In addition, the increment of the Location Quotient for grain yield was far greater than that of farmlands, resulting in a general increase in the SMIGF_A in these regions.

3.4. The spatio-temporal pattern of SMIGF_P

The spatio-temporal pattern of SMIGF_P presented a pattern of "northward and southward expansion" and "westward movement and northward expansion" during the two periods of 1990–2000 and 2000–2010, respectively (Fig. 7). (1) The inefficient farmland utilization regions are mainly distributed in the northern farming-grazing transitional zones and the southwest karst landform regions, as well as along the middle reaches of the Yangtze River. In 2000, the southwest karst landform areas realized a balance between grain yield and potential farmland resources. In 2010, this balanced pattern was broken. The southwest karst landform areas and the plain area in the middle reaches of the Yangtze River were the main districts experiencing population output. The phenomenon of the inefficient use of farmland resources was very common, so these regions' SMIGF_P showed a negative value. (2) For the main grain-producing areas, the spatial heterogeneity were very obvious. In 1990, the main grain-producing areas were mostly located in the Hunan Dongting Lake area, Jiangsu, Shandong and the Northeastern Plain. In 2000, the main grain-producing areas extended southwards to the border areas of Guangdong and Guangxi, and northwards to the Huanghuaihai Plain. In 2010, the main grain-producing areas showed a significantly trend of "westward movement and northward expansion". As a result, the main grain-producing function of the border areas of Guangdong, Guangxi and the Dongting Lake area declined significantly, while the regions with a higher grain-producing function expanded rapidly in the northeastern and northwestern areas.

By comparing the spatio-temporal patterns of SMIGF_A (Fig. 5) and SMIGF_P (Fig. 7), we found that the Huanghuaihai Plain and the northeastern regions became the main grain-producing areas in 2000 and in 2010, respectively, with the full exploration of farmlands' potential. Additionally, in 2010, the western region, with a water shortage, also began to undertake a grain-producing function. Contrarily, the SMIGF_A and SMIGF_P in the regions of the middle sections of the Yangtze River and Sichuan Basin varied greatly. The calculating result of SMIGF_A indicates that, in these two regions, the Location Quotient for grain yield was higher than that of actual farmland areas, and these were the main grain-producing areas in China. While the calculating result of SMIGF_P showed that, in these two regions, the grain yield and potential farmland areas realized a spatial matching, even in 2010, it appeared that the Location Quotient for grain yield was smaller than that for potential farmland areas, with seriously extensive and inefficient use of farmland resources. Finally, the relative grain yield was low, and these regions' function as main grain-producing areas declined. Therefore, we can see that the advantage of multi-crop systems in the middle reaches of the Yangtze River and Sichuan Basin has not yet been fully exploited, and the farmlands' potential has not yet been fully realized.

With the northern edge of the Yangtze River Valley as a boundary, the spatial distribution pattern of △SMIGF formed a north-south differentiation rule. The southern district possessed greater potential farmland resources, especially in the middle reaches of the Yangtze River, Sichuan Basin and Guangxi Basin. In contrast, the potential of farmland resources in northern areas was relatively low, especially in the northern farming-grazing transitional zones and in the northern Xinjiang. By comparing the spatial distributions of the grain-farmland mismatching regions with that of △SMIGF, we found that in 1990 and 2000, most main grain-producing regions were distributed in the areas with greater potential of farmland resources (△SMIGF > 0). In 2010, a serious phenomenon existed, whereby the main grain-producing regions shifted to the north. As a result, in the regions with greater farmland potential in Guangdong, Guangxi, the middle reaches of the Yangtze River and the Sichuan Basin, the grain-producing function deteriorated. Contradictorily, the northeastern area, Huanghuaihai Plain and the western region, all of which had lower farmland potential, became important functional zones for grain production. It was obvious that a great change in the grain-producing pattern of China has occurred. A large number of farmland in the south with multi-crop systems were abandoned. The grain barycenter shifted to the Huanghuaihai Plain and northeastern areas. Even Xinjiang, with a serious water shortage, gradually became the main grain-producing area of China. This kind of grain-producing pattern runs counter to the distribution patterns of potential farmland resources and water resources, and the spatial mismatch has increased the ecological risks.

4. Conclusions

Grain yield is simultaneously affected by farmland area and other external factors (fertilizers, irrigation, new species, new technology and mechanization). At the beginning of the 21st centrury, as the declining marginal efficiency provided by these external factors with regard to the level of grain production, farmland area again became the main constraint to increase the grain yield. So, retaining certain areas of farmland resources will become a paramount priority in assuring and maintaining China's food security.

However, the results of Gini coefficient and $\sum$SMIGF showed that, during 2000–2010, the spatial mismatch of grain yield and potential farmland resources has been aggravated by the grain production barycenter's shift to the north China with low Crop Rotation Index. The results achieved through an analysis of SMIGF_A and SMIGF_P prove that, since the 1990s, the main grain-producing areas in China have gone through two pattern changes of "northward and southward expansion" and "westward movement and northward expansion", respectively. In 2000, The regions with the greatest level of inefficient farmland utilization were mainly distributed in the northern farming-grazing transitional zones and northwest Xinjiang, where with fragile ecological environments. In 2010, the inefficient utilization of farmland extended to the southwest karst landform area. By comparing the spatial distributions of the main grain-producing areas and △SMIGF, we find that the northward shift of the main grain-producing areas resulted in the northeastern and northwestern regions with traditionally low producing potential to become the most important grain-producing areas in China. At the same time, the grain-producing functions of the plain regions in the middle reaches of the Yangtze River, Sichuan Basin and Guangxi Basin (areas which originally have greater producing potential) seriously deteriorated. These regions gradually became the areas with the most inefficient use of farmland.

5. Discussion

The spatial mismatch of the grain production and farmland resources in China is affected by many factors, including the external factors (such as urbanization, the rural-to-urban migration, irrigation technology and land remediation technology) and the natural factors (such as global warming) (Su et al., 2014b). Since the 1990s, the farmland resources have been occupied as a means to provide more development space for the towns and cities, expecting to experience a rapid urbanization (Su et al., 2011). In the areas where groups of cities were located, this phenomenon of farmland occupation was the most radical (Thompson and Prokopy, 2009; Jiang et al., 2013). This change of use of farmland is also leading to the decrease of grain-producing function in these areas (Su and Xiao, 2013). Simultaneously, the rural population has undergone a large-scale transfer to urban areas, and the phenomenon of the absence of agricultural management mainstream appeared which has further led to the inefficient use of and even the abandonment of farmland (Chen et al., 2014). This phenomenon is especially obvious in provinces which have experienced large population outputs, such as Sichuan and Hunan. The development of water-saving irrigation technology and the “South-to-North Water Diversion” Project, at least to a certain extent, has eliminated the restriction of water shortages on grain production in northern areas, thus improving the regions’ grain-producing efficiency (Chen et al., 2013a). Land remediation technology has allowed formerly saline-alkali lands and barren desert lands to be exploited as farmland. The saline-alkali land remediation in Huanghuaihai district helped the region to become the main grain-producing area in China at the beginning of the 21st century (Jiang, 2015). In addition, Global warming has led to a northward shifting of the grain-producing boundary in China. The crop system in the north has also been enhanced (Zhou and Turvey, 2014). In general, the above factors affect the farmland productivity.

However, the spatial mismatch between grain production and farmland resources also causes many problems, such as an imbalance in regional structures, ecological risks, agricultural production risks, and concerns over the price of food. The imbalance in regional structures is manifested as the imbalance of the main producing areas and the main selling areas. As the Chinese population migrates to the southeastern region, this region is becoming the main grain-selling area. This phenomenon is in strong spatial contrast to the pattern of the “westward movement and northward expansion” of the main grain-producing areas (Fan and Brzeska, 2014; Gandhi and Zhou, 2014). At present, the grain production pattern is inconsistent with hydrothermal conditions, which poses significant risks in terms of water and ecology. Due to the dry climate of the Xinjiang district, its irrigation coefficient on grain production reaches 80% (Brown and Waldron, 2013), resulting in a high dependence on groundwater, which in turn frequently causes an overuse of groundwater. The northeastern region has enlarged its farmlands area by reclaiming meadowlands and wetlands, which is rapidly leading to a decline in the ecological function of those wetlands. In addition, due to the overuse of black soil and irrational fertilization practices, the black soil is now facing ecological risks such as the reduction of the organic layer’s thickness and soil salinization (Gao and Liu, 2010). Meanwhile, large-scale north-to-south grain diversion increases the transportation cost of grain (Li et al., 2015). Confronted with the reality of low-priced imported grain, the “ceiling effect” of grain production in China is becoming more and more severe, with the grain production price risk increasingly highlighted.

In order to cope with the problems caused by the spatial mismatch between grain production and farmland resources, this paper provides some advice in view of actual conditions. As the contribution of farmland area to the improvement of grain yield is strengthened, farmland protection in terms of both quantity and quality will increasingly become the most fundamental measure to ensure the nation’s food security. For the sake of matching the spatial pattern of multi-crop rotation indices, with high levels in the south and low levels in the north, the farmland in South China which are of the highest quality should be preferentially categorized as basic farmland under permanent protection (especially in the plains of the middle reaches of the Yangtze River, Sichuan Basin and Guangxi Basin) (Lichtenberg and Ding, 2008; Ding, 2003). Only by that could we give full play to the advantage of multi-crop rotation planting and efficiently use the local rich hydrothermal resources, so as to improve the efficient use of farmland resources and gradually renew the grain-producing function of South China (Su et al., 2016). Conversely, in the regions with the fragile ecological environment, such as the northeastern area and West China, based on the water, soil and climatic conditions, the crop rotation system should be decided upon scientifically. Drought-tolerant crops should be planted, and the ground water should be recovered by means of leaving lands fallow and rotating crops.

In addition, in view of the inefficient use and even abandonment of farmland caused by population outflow, and given the opportunity presented by migrant workers returning home due to the economic decline, the Chinese government should actively provide the returning farmers with help and support in terms of financing, training in agricultural techniques, and so on. Such policies would make it possible for the migrant workers to again throw themselves into grain production. In addition, the government should encourage the returing farmers to extend the industry chain by taking advantage of their more advanced social resources and market consciousness than the local farmers have at present. It makes sense to build the grain industry chain by integrating “production-processing-logistics distribution”, promoting the integrating development of the primary, secondary and tertiary industry, increasing the additional value of the grain industry, and ensuring food security. Such policies would at the same time help with the reemployment and increase the income of migrant workers who are returning home. To ensure the implementation of the above-mentioned regional policy suggestions, it would also be necessary for China to reform and innovate some aspects of its agricultural policies, such as creating a rural land circulation system, grain price forming mechanism, farmers’ subsidy policy and a grain collection and storage policy. Such practices, if implemented, would protect the farmers’ benefits, ensure the stability of grain prices, promote large-scale land management and commonly defuse the food security issues currently facing China.

Finally, under the background of radical barycenter shift of grain production, it is important to point out that appropriate policies should be issued in different regions, which give fair amount of consideration to cost factor along with benefits. As we all know, external factors are important since they bear cost implications. And the marginal effects of external factors are also affected by natural factors. The hydrothermal conditions in the northern region are congenitally deficient (Dong et al., 2011), and the northward shifting of the grain-producing barycenter, at least to a certain extent, increases the overall cost of grain-production. Thus, the specific policy should be released in each region according to their external factors and natural factors, so as to save the additional cost and achieve the maximized efficiency.

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