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Spatio-Temporal Pattern Change of Winter Wheat Production and Its Implications in the North China Plain

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Abstract: The North China Plain (NCP) is the most important winter wheat production region and an area of water shortage in China. The stability of winter wheat (*T. aestivum L.*) production in spatial pattern and the sustainability of water resources have been a major policy concern in China. This study explored the barycenter shift and change trends of wheat total production during 1998–2015, using methods of barycenter model, Sen's slope, and Mann Kendall test, and analyzed the influence of external factors and the response of water resources. Results indicated that the barycenter of wheat production moved southwards by 115.16 km during 1998–2015, with an average speed of 6.77 km/year. For the entire NCP, the total production showed phased changes during the study period: It decreased during 1998–2003, and then continuously increased during 2004–2015. Of the wheat production increase in the NCP, yield increase and sown area expansion averagely contributed 64.5% and 35.5%, respectively, and the contribution proportion of yield increase continuously increased since 2003. At county level, total wheat production showed a significant increase and decrease trend in 87 and 29 counties, mainly distributed in the southern and northern NCP, respectively. The increase of total production at county level was mainly contributed by yield growth in the southern NCP, while the decrease in the north was due to the reduction of sown area to great extent. The southward shift was jointly resulted by the spatial variation of input factors, benefit, and water prices. These spatial pattern changes alleviated the water pressure in the north region to some extent, in the case of ensuring the production increase of winter wheat. Therefore, the current spatial shift should be continuously promoted in the future.

Keywords: winter wheat; spatial pattern; production barycenter; water resources; the North China Plain

1. Introduction

China's food security is always a worldwide concern due to the huge population and large food demand [1]. Spatial pattern changes in grain production are closely related to food security, and have caused widespread attention [2,3]. Past studies have analyzed the spatial pattern of grain at the country and province level such as Henan [4], Heilongjiang [5], and Jiangxi in China [6], and found that the barycenter of grain production shifted from southern to northern China [3,7,8]. However, no analysis was found on grain production pattern changes in major grain producing area. In view of the situation that water resources and cultivated land are not well matched between the North and the South in China, i.e. the population and cultivated land area in northern China accounts for 52% and 60% of the total, respectively, but water resources account for only 21.3%, thus the northward shift of grain production may bring more severe water resources problems. A more serious situation exists in the North China Plain (NCP), where cultivated land area accounts for about 39.4% of China, but its water resources cover only 7.7% [9]. Further, the groundwater resources were depleted increasingly since 1960s, due to the agricultural development. The contradiction of grain production increase and groundwater resources decrease in the NCP has always been a policy concern in China [10,11].

Second only to rice, winter wheat is the most important ration in China with its production and sown area being 12.74 Mt and 22.62 Mha (China Statistical Yearbook). As the most important production area of winter wheat in China, the NCP produced 71.3% of the total wheat production with 53.2% of total sown area in 2015. The spatial pattern stability of winter wheat production in the NCP is of great significance to China's food security. However, winter wheat is the most irrigation demanding crop and consumes more than 50% of the total irrigation water. As wheat production heavily relies on irrigation from groundwater resources [12–15], the large production in the NCP that was mainly attributed to the expansion of irrigated area and increase of water supply per unit sown area has caused serious depletion of groundwater, especially in the northern NCP with scarce water resources [16–18]. During the last decades, the local governments took some measures to relieve this problem by reducing sown area of winter wheat, and thus could induce the spatial pattern changes of winter wheat production and might affect stability of wheat total production in the NCP [12,14,19–23].

Therefore, to serve the priority setting of grain production and water resource use, an analysis is necessary to understand the spatial pattern of grain production and its causal factors in the NCP. The purposes of this study are to reveal the spatial pattern change of winter wheat production in the NCP during 1998–2015, and to discuss the influence of external causal factors and the response of water resources, which would contribute to understanding the sustainability of both winter wheat production and water resource use in the NCP. With those aims, we firstly analyzed the barycenter shift of total wheat production during 1998–2015 and the change trends at both region and county levels, using the barycenter model, Mann Kendall (MK), and Sen's SLOPE methods, and then calculated the contribution rates to total production by yield and sown area at both levels. Finally, the spatio-temporal changes of external causal factors and the response of water resources were analyzed.

2. Materials and Methods

2.1. Study Sites

The NCP, also known as the Huang-Huai-Hai Plain, comprises the basin of the Yellow River, the Huaihe River, and the Haihe River in China, including the plain areas of Beijing, Hebei, Shandong, and Henan, the northern parts of Anhui and Jiangsu, and the whole Tianjin Municipality [24] (Figure 1). It involves a total of 327 counties, with the land area of 39.4 Mha and population of about 280 million. In 2015, more than 80% of land area in the NCP was cultivated, and more than 90% of farmland was with irrigation facility. Winter wheat and summer maize (*Zea mays L.*) are main crops, normally grown in a double crop rotation. In the NCP, the average annual precipitation ranges from 501.2 to 1325.0 mm, increasing from north to south. Of the annual precipitation, 75–83% falls in maize growing period (from June to September), and only 17–25% falls in wheat growing season (Figure 2). In the NCP, an average of 78.8% of the total water consumption is used for agriculture irrigation, and more than 50% of which is for winter wheat due to the rather scarce rainfall during its growing period [25,26]. Since the 1960s, the depletion of groundwater resources in the northern NCP was aggravated by the increasing sown area of winter wheat, for instance, the groundwater level in the Beijing-Tianjin-Hebei region decreased by 20–40 m. Water resources have become the main constraint for agriculture production [10,24,26,27].

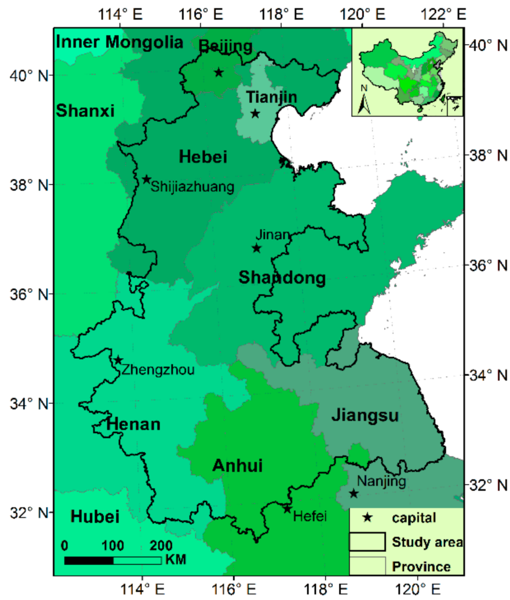

Figure 1. Location and extent of the North China Plain.

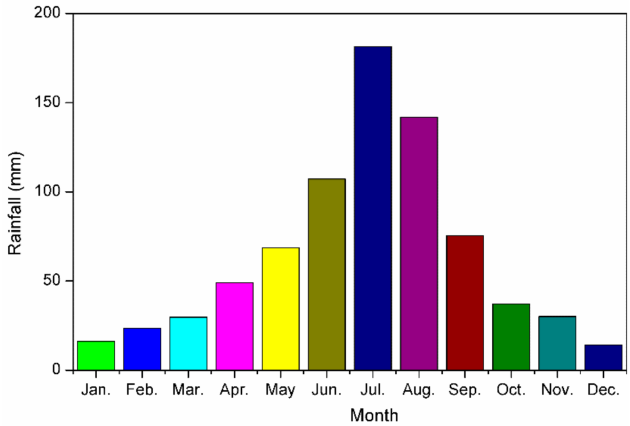

Figure 2. Monthly variation of average rainfall during 1998–2015 in the North China Plain.

2.2. Data Source

County-level production data of winter wheat in the NCP were collected from the city yearbook and the provincial rural statistical yearbook during 1998–2015, including total wheat production, sown area, yield, irrigated area, fertilizer application, and total agricultural machinery power (Table 1). For the case where the data of individual counties were missing, the average values of adjacent four years were used for interpolation. For the counties with administrative boundary change such as Kaifeng, Tongshan, and Shouxian, the data are based on the adjusted administrative units. Input costs and market prices of winter wheat were sourced from the compilation of national agricultural product cost and income data during 1998–2015, published by the China Price Press. Furthermore, agricultural water use, total groundwater resources, and groundwater level in different regions of the NCP were collected from the China Water Resources Bulletin and the China Groundwater Dynamics Monthly, released by the Ministry of Water Resources during 1998–2015.

Table 1. Data source of winter wheat production at county level in the North China Plain (NCP) during 1998–2015.

Data Information	Provincial Yearbook	City/ Municipality Yearbook
Total production, sown area, yield, irrigated area, fertilizer application, and total agricultural machinery power	Hebei rural statistical yearbook, Henan statistical yearbook, Anhui statistical yearbook, Jiangsu statistical yearbook	Beijing, Tianjin, Binzhou, Dezhou, Heze, Liaocheng, Linyi, Taian, Jining, Jinan, Weifang, Dongying, Zaozhaung, Zibo, Shijiazhuang, Baoding, Hengshui, Langfang, Cangzhou, Tangshan, Xingtai, Qinhuangdao, Langfang, Lianyungang, Suqian, Xuzhou, Yancheng, and Huaian

2.3. Barycenter Model

The barycenter model was widely used to present spatial trend changes of geospatial factors in certain region and period [3,7,28–30]. The barycenter model is expressed by the equations as follows:

$$x_j = \frac{\sum_{i=1}^{n}\left(T_{ij}\cdot x_i\right)}{\sum_{i=1}^{n} T_{ij}} \tag{1}$$

$$y_j = \frac{\sum_{i=1}^{n}\left(T_{ij}\cdot y_i\right)}{\sum_{i=1}^{n} T_{ij}} \tag{2}$$

where i and j are serial numbers of counties and years, T_{ij} is the total production of the i-th year and j-th county. x_i and y_i are longitude and latitude of the geographic barycenter of each county. x_j and y_j are longitude and latitude of the production barycenter in the entire NCP.

Suppose that the coordinate of barycenter in m-th and $(m + n)$-th year in the NCP were (x_m, y_m) and (x_{m+n}, y_{m+n}), the barycenter shift distance is expressed with d_n, which is calculated with Equation (3) [3,7].

$$d_n = \sqrt{(x_{m+n} - x_m)^2 + (y_{m+n} - y_m)^2} \tag{3}$$

2.4. Change Rate Estimation Method

The MK non-parametric rank test determines whether data sequences change significantly based on two variables, S and Z. The S, expressed as $S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn\left(X_j - X_i\right)$ (i = 1, 2, . . . , n − 1), is the summation of sgn(X_j-X_i), which is valued as −1,0, and 1, when $(X_j - X_i)$ is less than, equal to, and more than 0, respectively. Z value is the normalized test statistic check value of the S, when S > 0, Z = (S − 1) / σ, and when S = 0, Z = 0, when S < 0, Z = (S + 1) / σ, where σ = n (n − 1) (2 n + 5)/18 [31,32]. In this test, at given confidence level α, $|Z| \geq Z_{1-\alpha/2}$ signifies a significant increasing or decreasing trend [33]. In this study, the α was set to 0.1 and 0.5 to identify the significance of production changes.

The change rate was estimated using the Sen's slope method. It is a consistent non-parametric estimation of coefficients obtained from linear regression of sequence data and can reflect change magnitude accurately [33]. Together with the MK test, the slope value of production data in each county was calculated to reveal spatial variation characteristics at county level in the NCP (Equations (4)–(6)) [34].

$$Y(t) = SLOPE\cdot t + c \tag{4}$$

$$SLOPE_i = \frac{Y_j - Y_k}{j - k} \tag{5}$$

$$SLOPE = \begin{cases} SLOPE_{\frac{(N+1)}{2}} & N \text{ is odd} \\ \left(SLOPE_{\frac{N}{2}} + SLOPE_{\frac{(N+2)}{2}}\right)/2 & N \text{ is even} \end{cases} \tag{6}$$

where c is the constant term, i denotes the serial number of counties, and j and k denotes years ($j > k$). $SLOPE_i$ is the Sen's slope value of total production, sown area, or yield of i-th county, and Y_j and Y_k are the variables in j-th and k-th year, respectively. N is the time duration.

2.5. Contribution Rate Decomposition model

The variable decomposition method is often used to calculate the contribution rates to total production change by yield and sown area [35]. The model equations are shown below:

$$CY_{i,n+1} = (Y_{i,n+1} - Y_{i,n}) * A_{i,n} / (P_{i,n+1} - P_{i,n}) \tag{7}$$

$$CA_{i,n+1} = (A_{i,n+1} - A_{i,n}) * Y_{i,n+1} / (P_{i,n+1} - P_{i,n}) \tag{8}$$

where $CY_{i,\,n+1}$ and $CA_{i,n+1}$ are the contribution rates to total production change by yield and sown area; i and n are the serial numbers of counties and years, respectively, and i = 1,2,...I (I = 327); n = 1,2 . . . N (N = 17). $Y_{i,\,n}$ and $Y_{i,\,n+1}$ are the winter wheat yields of the i-th county in n-th and $(n+1)$-th years; $A_{i,\,n}$ and $A_{i,\,n+1}$ are the sown area of the i-th county in n-th and $(n+1)$-th years; $P_{i,\,n}$ and $P_{i,\,n+1}$ are the total production of the n-th and $(n+1)$-th year of the i-th county, respectively.

3. Results and Discussion

3.1. Pattern Changes of Total Production

3.1.1. Barycenter Shift

From 1998 to 2015, the barycenter of total production in the NCP shifted southward significantly. The longitude of the barycenter shifted slightly between 115°57′–116°10′ E, while the distance of latitude shift from north to south was rather long, ranging from 35°0′ to 35°40′ N (Figure 3). The total shift distance was 115.16 km, with a speed of 6.77 km/year. The shift distance varied among different periods: It was shifted southward by 42.84 km during 1998–2002, slightly increased to 51.59 km during 2003–2007, then dramatically decreased to 12.78 km during 2007–2011, and 7.95 km during 2012–2015. Accordingly, the shift speed decreased from 10.70 during 1998–2002 and 10.32 km/year during 2003–2007, to 3.20 km/year during 2008–2011, and to 1.99 km/year in the last four years (Table 2). In addition, the barycenter showed a significant southward shift during 1998–2007 and 2012–2015, while it showed a northward shift to some extent during 2008–2011.

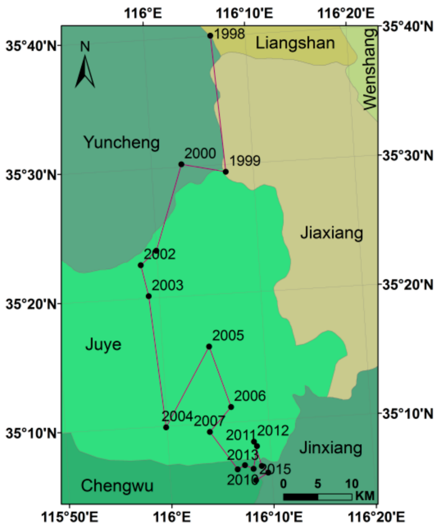

Figure 3. Shift path of winter wheat production barycenter in the North China Plain during 1998–2015.

Table 2. Shift distance and orientation of winter wheat production barycenter in the NCP during 1998–2015.

Periods	1998–2002	2003–2007	2008–2011	2012–2015	1998–2015
Distance (km)	42.84	51.59	12.78	7.95	115.16
Speed (km/year)	10.70	10.32	3.20	1.99	6.77
Orientation	Southwest	Southeast	Northeast	Southeast	Southeast

The continuously southward shift of the wheat production barycenter in the NCP was caused by the regional wheat production changes [8]. We analyzed the change trends in the seven provinces involved in the NCP and found that the production proportion in north provinces was decreasing, while it was increasing in south provinces (Figure 4). In the initial year of 1998, the proportion of total wheat production in Beijing, Tianjin, and Hebei of the north region was 1.72, 1.38, and 24.16%, but dramatically declined to 0.13, 0.76, and 15.91% in 2015, with average change rates of −0.066%/year (R^2 = 0.610, p < 0.01), −0.027%/year (R^2 = 0.556, p < 0.01), and −0.448%/year (R^2 = 0.857, p < 0.01), respectively. The proportion of winter wheat production in the central region had minimal changes: It was generally unchanged at about 23.50% in Shandong, and increased slightly from 29.50 to 31.34% in Henan. In the south region, including Jiangsu and Anhui provinces, the proportion significantly increased from 9.53 and 12.60 to 11.36 and 16.71%, with the average change rates of 0.133%/year (R^2 = 0.660, p < 0.01) and 0.338%/year (R^2 = 0.790, p < 0.01), respectively (Table 3).

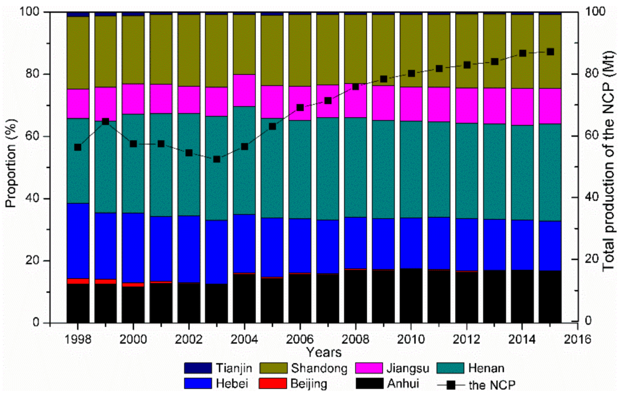

Figure 4. Total production of winter wheat in the North China Plain and the proportion of total production in each province (municipality) during 1998–2015.

Table 3. Trend changes of the proportion of wheat total production in the whole North China Plain at province level from 1998 to 2015.

Items	Hebei	Beijing	Tianjin	Shandong	Henan	Jiangsu	Anhui
SLOPE (%/year)	−0.448	−0.066	−0.027	0.078	−0.007	0.133	0.338
R^2	0.857	0.610	0.566	0.146	0.005	0.660	0.790
Sig.	**	**	**			**	**

*** indicates significant (p < 0.01), ** indicates significant (p < 0.05) and * indicates significant (p < 0.10).

These results differed in shift orientation and speed from other studies. For instance, Xu et al. analyzed the spatio-temporal patterns of grain production in China during 1995–2007 and found that the barycenter moved by 254.7 km towards the northern and eastern regions with a similar speed of 8.0 km/year [7]. Wang et al. indicated that the grain production barycenter moved towards northeast by 260.64 km during 2003–2014 in China with a higher speed of 21.72 km/year [3]. The analysis results of the barycenter shift of winter wheat and maize during 2000–2012 in China indicated that the winter wheat production barycenter hovered in a small range, while the maize production shifted northward [8]. The reason was due to the significant increase in maize production in the north, especially the rapid expansion of maize sown area in the north bank of the Yellow River basin. The main reason is that maize crop growth needs less water from irrigation than wheat, because more rainfall can supplement its water demand (Figure 2). Meanwhile, local government in the north raised irrigation prices to reduce water utilization. As a result, more and more households there tend to fallow the farmland in wheat season and prefer to plant maize to obtain more benefits [36].

3.1.2. Trend Analysis

From 1998 to 2015, the total production of winter wheat in the NCP increased from 56.27 to 87.22 Mt with an annual average increase rate of 2.79%. Except for the period of 1998–2003, during which wheat production decreased from 56.27 to 52.66 Mt, it has kept a continuous growth since 2004. In 2015, the total wheat production reached 87.22 Mt (Figure 4).

The main reason was that in 1999, the government initiated and implemented the Grain for Green Project to mitigate the land degradation problems by returning steeply sloping croplands to forests or grasslands [37,38] with attractive subsidies (money and grain) for the conversion. This policy stimulated an over-conversion of farmlands [39,40], and thus adversely affected farmer's enthusiasm for grain production. Recognizing this problem, the Chinese government strictly regulated the scope of farmland conversion in 2004, and meanwhile implemented a series of policy measures, including the exemption of agricultural taxes for the first time in China's history, increase of direct subsidies to crop production, and liberalization of market of production materials and crop products. These policies greatly mobilized the famer's enthusiasm and improved the benefits of crop production, stimulating agricultural inputs, thus, resulting in yield increase. This could be the reason why total production and yield of winter wheat in the NCP showed a quick rise since 2004 (Figure 4) [37,38].

Further analysis at county level showed that the total wheat production increased in 85.6% of the counties. In 87 counties (26.6%), mainly distributed in the southern NCP, the mean growth rate (SLOPE value) of total production exceeded 10.0 Kt/year, and in 193 counties (59.0%), located in the central regions, it was between 0–10 Kt/year. In the remaining 47 counties concentrated in the north of the Hebei province (Figure 5a), it showed a decrease trend (the SLOPE value was minus). In 48 counties (14.7%), mainly distributed in the south Anhui and Jiangsu provinces, the annual growth rate exceeded 5.0%, in 112 counties (34.3%) it ranged 2.5–5.0%, and in 120 counties (36.7%) it was less than 2.5% (Figure 5b). In the 47 counties with production decreases, 38 counties (mainly located in the Beijing-Tianjin-Hebei region) showed a significant decrease trend ($Z \leq -1.645$) in the total wheat production, and 9 counties an insignificant decrease trend ($-1.645 < Z \leq -0.675$).

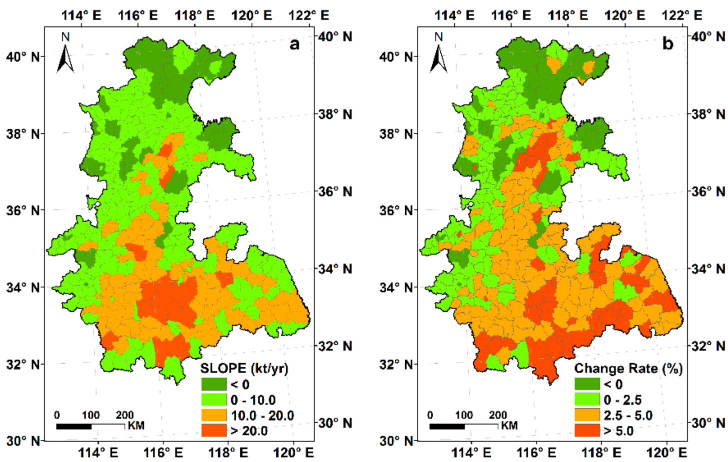

Figure 5. The spatial distribution of SLOPE values (**a**) and annual average change rates (**b**) of total winter wheat production at county level in the North China Plain from 1998 to 2015 (the change rate in Figure b is the ratio of SLOPE value to the average of production during 1998–2015).

3.2. Contribution Rates to Total production by Yield and Sown Area

3.2.1. Change Trends of Yield and Sown Area

From 1998–2015, the sown area of winter wheat in the NCP increased from 12.04 Mha to 12.28 Mha, with a speed of 0.51% per year. Yield increased from 4.67 to 6.72 t/ha, with a speed of 2.27% per year, much higher than that of the sown area. Similar to the total wheat production, the yield and sown area also showed a phased change. During 1998–2003, total wheat production and sown area decreased by 6.9% and 12.8%, respectively, and then all increased continuously from 2004 to 2015.

At county level, the sown area of winter wheat decreased in 88 counties, mainly located in the north. In 170 counties, mainly distributed in the southeast and center regions, the sown area increased by more than 1.0 Kha per year, and in the remaining 69 counties, scattered in the central and northern regions, it increased insignificantly (Figure 6a). Regional difference of yield was smaller than that of sown area. Yield showed an increase trend in more than 95% of counties, except in a few counties in the northeast. The SLOPE values of yield in counties of the south were higher than those in the north, especially in the southwest, where the yield increased by more than 100.0 kg/ha per year (Figure 6b).

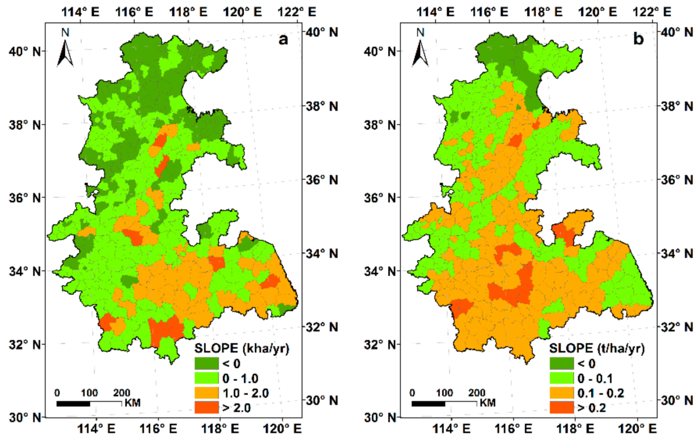

Figure 6. The spatial distribution of SLOPE values of the sown area (**a**) and yield (**b**) of winter wheat in each county of the North China Plain from 1998 to 2015.

3.2.2. Contribution of yield and sown area to total production

Of the total wheat production change in the NCP, 64.5% was contributed by the yield increase, and 35.5% by the sown area expansion. Linear regression results showed that the contribution of sown area was higher than yield before 2003, but it became lower since 2004 with the gap widening gradually. In the last 5 years, the yield contribution increased to 96.3%, while the sown area contribution decreased to only 3.7% (Figure 7).

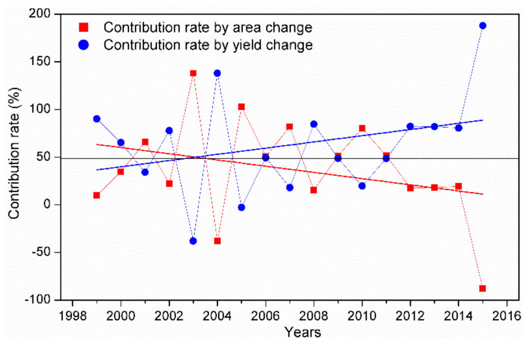

Figure 7. Contribution rates to total wheat production by changes of yield and sown area in the North China Plain from 1998 to 2015 (the sum of contribution rate by yield and sown area is 1).

At county level, the contribution rates by yield and sown area during 1998–2015 were rather similar to that at regional level. Yield change contributed more than 50.0% of the change in total production in 185 counties, mainly distributed in the central and the southwestern NCP, while it ranged from 50.2 to 99.1% in 89 counties, and exceeded 100.0% in the other 96 counties (Figure 8a). Correspondingly, the contribution rate by sown area was more than 50.0% in 142 counties, mainly located in the northeast and southeast. In 93 counties, it was between 50.1 and 99.3%, and in 49 counties, it was more than 100.0% (Figure 8b). In general, the total production increase was mainly contributed by the improved yield in the southern NCP, while the production stagnation or decrease in the north was due to the reduction of sown area to great extent.

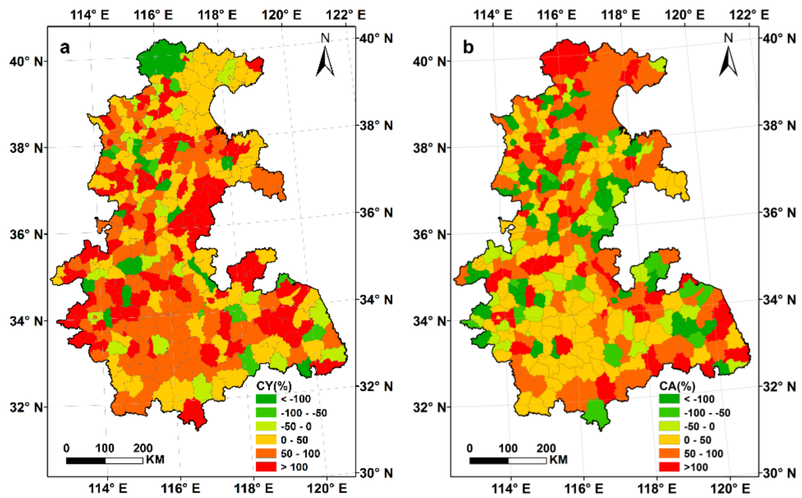

Figure 8. Average contribution rates to the total wheat production change by yield (**a**) and sown area (**b**) at county level in the North China Plain during 1998–2015 (the sum of contribution rate by yield and sown area is 1).

3.3. External Causal Factors Analysis

3.3.1. Input Factors

Input factors are major driving forces of the spatial shift of grain production, as grain production is closely related to the input factors [36,41,42]. We analyzed statistical data of winter wheat input factors during 1998–2015 and found that there were significant differences in the changes of irrigation, chemical fertilizer application, and total mechanical power in different regions of the NCP. For instance, the irrigated area increased by only 2.9% in Hebei and even decreased slightly in Beijing and Tianjin from 1998 to 2015, while it increased by 44.3 and 20.3% in Anhui and Henan, respectively. The amounts of fertilizer application in Hebei and Shandong increased by 24.2 and 14.0%, much lower than that of Henan (87.1%) and Anhui (33.5%). The increases of agricultural machinery power in Anhui and Henan were 158.4 and 145.8%, much higher than that in Hebei. The barycenter of all these factors also showed a trend of southward shift but no significant change trend in longitudes (Table 4), which were consistent with the shift orientation of winter wheat production. The correlation analysis results showed that there were significant correlations between the latitude coordinates of wheat production barycenter and irrigated area ($R^2 = 0.422$, $p < 0.01$), total agricultural machinery power ($R^2 = 0.783$, $p < 0.01$), and fertilizer application ($R^2 = 0.493$, $p < 0.01$), respectively (Figure 9).

Furthermore, the spatio-temporal variation of winter wheat production might also be affected by the genetic characteristics of crop varieties. However, more than 100 varieties of winter wheat were planted in the NCP from 1998 to 2015, and they were all scattered in different local regions irregularly (http://www.chinaseed114.com/seed/137/). Due to the lack of more detailed data, the influence of varieties was not considered in this study.

Table 4. Barycenter coordinates of irrigated area, agricultural machinery power, and fertilizer application in the NCP during 1998–2015.

Year	Irrigated Area		Agricultural Mechanical Power		Fertilizer Application	
	Longitude (Degree)	Latitude (Degree)	Longitude (Degree)	Latitude (Degree)	Longitude (Degree)	Latitude (Degree)
1998	116.86	35.33	116.61	35.96	116.88	35.02
2002	116.80	35.29	116.62	35.86	116.75	34.97
2006	116.78	35.27	116.55	35.79	116.68	35.00
2010	116.76	35.24	116.54	35.69	116.51	34.93
2015	116.78	35.05	116.57	35.58	116.40	34.90

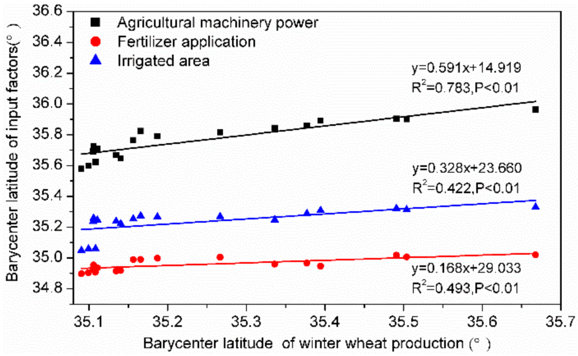

Figure 9. The relationship between the latitude coordinates of the barycenter of winter wheat production and irrigated area, fertilizer application, and agricultural machinery power during 1998–2015.

3.3.2. Wheat Production Benefit

Planting benefit affects crop production indirectly [43–45]. To identify its impact on the change of production pattern, we calculated and mapped the net return per unit area of winter wheat in 327 counties in 1998 and 2015, respectively. In 1998, the net return in southern counties were generally low, and 147 counties with rather high net return (>2000 yuan/ha) were mainly located in the northwest and north (Figure 10a). In 2015, net return was much lower in the north counties than the south. Net return was more than 2000 yuan/ha in 239 counties, most of which were distributed in the central and southern regions (Figure 10b). By comparing their changes from 1998 to 2015, we found that the net return decreased by 18 to 4800 yuan/ha in 103 northern counties. In 224 counties with increasing net return, the increase amplitude was between 86 and 3977 yuan/ha in the most counties of the central and southeastern regions. The increase amplitude exceeded 4000 yuan/ha in 64 counties, mainly located in the southwestern region (Figure 10c).

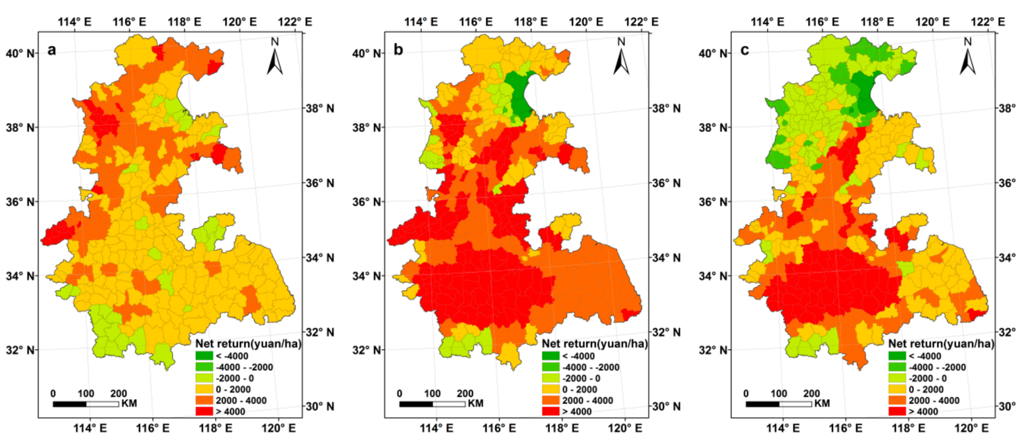

Figure 10. Spatial distribution of net returns of winter wheat of 1998 (**a**), 2015 (**b**) and their differences (**c**) in the North China Plain.

The decline in planting benefit in the north NCP is mainly attributed to the increase of agricultural material prices, for instance, the current prices of machinery service, labor, fertilizer, pesticide, and irrigation in 2015 increased by 209.8, 270.2, 67.0, 218.4, and 93.3% compared with that in 1998, respectively. Affected by these changes, agricultural materials input by households to winter wheat increased rather slowly or stagnated. As a result, a large plenty of farmers even abandoned planting winter wheat instead of fallowing the farmland and prefer to plant maize to obtain more benefits, resulting in a downward trend in the sown area and total production of wheat. In the south NCP, however, the benefit increased due to the continuous yield increase, as well as the rather low irrigation price. The increasing benefit drove the household input for more agricultural material, which would further increase the benefit by improving the yield of winter wheat. The spatial distribution and amplitude of net return change could partly explain why the barycenter shift southwards in the NCP.

3.3.3. Agricultural Irrigation Policies

In the NCP, irrigation is an important guarantee to meet water demand for crop growth and production of winter wheat, due to scarce water resources and low precipitation [15,17,20,46]. In the 1960s, the government gave priority to food security, and actively advocated the development of irrigation facilities and implemented free use of irrigation water (only agricultural electricity fee was needed) [37]. These policies were conducive to the increase of grain production, but also brought over-use of groundwater in the northern NCP.

In recent years, to cope with the increasing shortage of groundwater resources in the northern NCP, the government took some measures to reduce the exploitation, such as raising water prices in over-exploited areas, encouraging the land in fallow after harvesting maize, and expanding maize planting area [14]. Under the influence of these policies, the average irrigation price in Hebei Province significantly increased from 30.4 to 69.1 yuan/ha during 18 years, which is higher than that of southern provinces such as Henan and Anhui (Figure 11). In 2017 and 2018, we did investigations in 21 counties and cities of NCP, and found that the situation was more severe, i.e. irrigation price in the north counties such as Tangshan, Cangzhou, and Shijiazhuang were more than three times higher than that of Zhoukou, Shangqiu, and Zhangzhou in the south. As a result, the sown area and total production of winter wheat decreased sharply in the northern NCP, due to that many farmers have reduced irrigation times and water amount [11,20,47]. In southern regions, water resources were sufficient to raise winter wheat production.

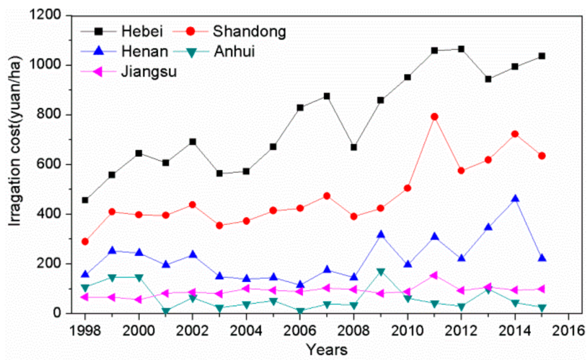

Figure 11. Variation of irrigation costs in some provinces of North China Plain during 1998–2015 (the yearly prices for calculating costs in the figure indicate the current prices).

3.4. Implications

Southward shift of wheat production during 1998–2015 significantly reduced the agricultural water use in the northern NCP. The China Water Resources Bulletin reported that in 1998, 2006, 2010, and 2015, water consumptions for agriculture in the Haihe River Basin was 30.74, 27.47, 24.76, and 22.60 billion m^3, accounting for 72.5%, 70.3%, 67.2%, and 62.2% of the total use, and 30.77, 28.26, 27.76, and 27.27 billion m^3, accounting for 77.9%, 73.8%, 70.8%, and 69.9% in the Yellow River Basin, respectively. These decreasing trends reduced the pressure on water resources in the northern NCP, contributed to the restoration of groundwater resources. In these four years, the total groundwater resources increased steadily from 15.50, 18.91, 22.44, to 25.9 billion m^3 in the Haihe River Basin, and 17.90, 35.78, 38.52, to 35.49 billion m^3 in the Yellow River Basin, respectively. As a result, the groundwater level withdrawal stopped in the northern NCP in recent years (China Groundwater Dynamics Monthly).

The southward shift of winter wheat production has relieved the pressure of water resources in the north part, while still ensuring the increase of winter wheat production in the whole NCP. It should be noted that groundwater resources are not abundant in the northern NCP, and some cities such as Tianjin, Shijiazhuang, Xingtai, Zibo, and Anyang are still suffering from severe water shortage problem. Therefore, it is necessary to further promote the southward shift of wheat production in the NCP. Meanwhile, water-saving technologies should be extended to ensure the sustainable water resource use.

4. Conclusions

This study explored the spatial pattern changes of winter wheat production during 1998–2015, and discussed the influence of external factors and the response of water resources in the NCP. The results indicated that:

(1) Contrary to the northward shift of grain production in the entire China, the barycenter of winter wheat production in the NCP moved southwards by 115.16 km from 1998 to 2015, with an average speed of 6.77 km/year. The southward speed was more than 10 km/year during 1998–2002, and then slowed down to 1.99 km/year during 2012–2015.

(2) Total wheat production in the entire NCP showed phased changes during the study period: it was decreased or stagnated during 1998–2003, and then significantly increased from 52.36 to 86.22 Mt since 2004. Most counties (85.6%) showed a similar trend. A total of 87 counties mainly distributed in the southern NCP showed a significant increase trend in wheat production, while 38 counties mainly distributed in the northern NCP a decrease trend.

(3) Of the total wheat production increase in the NCP, 64.5% and 35.5% were contributed by yield increase and sowing area expansion, and the contribution of yield increase was enlarged greatly since 2003. In general, the total production increase of winter wheat was mainly contributed by yield increase in the southern counties, while the decrease of total production in the north was mainly due to the reduction of sown area.

(4) The change of winter wheat production pattern jointly resulted from spatial changes of input factors, net returns, water prices, and benefit. Water pressure in the northern NCP was alleviated to some extent, with the southward shift of wheat production.

(5) The north part of NCP is densely populated. To meet the water requirement, it must improve the water use efficiency by adopting more strict water management policies and water saving technologies. In addition, to promote the further southward shift of wheat production could be a good option to reduce the agricultural use of limited water resources, while still maintain a sustainable production of wheat.

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