Spatial Pattern of Winter Wheat Production and Its Controlling Factors in Hebei Province: A Postprint

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Abstract

Against the backdrop of climate change and water resource scarcity, winter wheat production in the North China Plain faces enormous challenges. Clarifying the spatial pattern of winter wheat production and its controlling factors can provide a basis for scientific planning, management decisions, and efficient production of winter wheat in this region. Based on winter wheat yield per unit area and agricultural data from 2004–2013 for various counties and cities in Hebei Province, 101 counties and cities in the main production area (selected based on the criterion that the average winter wheat sown area in a county/city exceeds 20% of the total sown area) were used as the basic research units. Systematic cluster analysis was employed to divide the main winter wheat production areas in Hebei Province into regions; factor analysis was used to conduct principal component analysis of winter wheat production factors, and stepwise regression analysis was used to establish the relationship between winter wheat yield and principal components of the main controlling factors. The results show that the main winter wheat production areas in Hebei Province can be divided into four regions (I–IV), with winter wheat yield levels decreasing sequentially from Region I to Region IV, yield variation increasing sequentially, and differences among all regions reaching significant levels ($P<0.05$). Winter wheat yield (Y) has a significant linear regression relationship with fertilizer factor (F1), irrigation factor (F3), annual precipitation factor (F4), and lower limit of annual precipitation factor (F5) ($R2=0.685$, $P<0.05$), where F1 and F3 explain 21.7% and 37.4% of Y, respectively, and F4 and F5 explain 9.4% of Y. This indicates that irrigation is the primary factor influencing regional differences in winter wheat yield in Hebei Province, followed by fertilizer application rate, while annual precipitation has a relatively minor impact on regional yield differences. The regression effect of pesticide factor (F2) is not significant, indicating that the occurrence and control of winter wheat pests and diseases have regionally random variation characteristics and do not exert a significant influence on

regional differences in winter wheat production. Additionally, there is good regional congruence between the proportion of winter wheat sown area and yield level across the province (R2=0.409, P<0.05), indicating that the regional distribution of winter wheat is basically reasonable under the current management model. However, the sown area is significantly high in very few low-yield counties in the eastern low plain coastal area. Considering the dependence of winter wheat on irrigation conditions, it is believed that the winter wheat distribution in these counties and cities requires careful reconsideration.

Full Text

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Spatial Structure and Control Factors of Winter Wheat Production in Hebei Province*

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Abstract

Winter wheat is one of the most important staple crops in the North China Plain. With intensifying challenges of climate change and water shortage, the need for sustainable and high-efficiency winter wheat production is becoming more pressing. A clear understanding of the control factors of wheat production can provide the necessary basis for regulating smart winter wheat production policies. Hebei Province is one of the major winter wheat production regions in North China.

Annual records (2004–2013) of wheat yield and agricultural information for each county in the province were used to analyze the spatial distribution of yield variation of winter wheat along with its control factors. The major winter wheat production area (consisting of 101 counties with winter wheat area greater than 20% of total cropping area) in Hebei Province was selected and divided into four zones (–) using hierarchical clustering analysis based on maximum, minimum, and average yields. A principal component analysis was conducted using the average and variation indexes (minimum, maximum, and the bottom and top boundaries of the 95% confidence interval) of agricultural variables for winter wheat production, including irrigated area, fertilizer and pesticide amounts, and annual rainfall in each county. Five derived principal factors represented fertilizer (F1), pesticide (F2), irrigation (F3), annual rainfall (F4), and minimum rainfall (F5). Based on the factor score values, a stepwise regression analysis model was developed to assess the spatial variation of winter wheat yield as an independent factor (Y). The results showed that from Zone to Zone , average winter wheat yield decreased while temporal yield variation increased significantly ($P < 0.05$). Zone mostly covered the central Hebei Plain, including Gaocheng and Luancheng Counties to the east of Shijiazhuang City. Zones , , and diverged from the central to the peripheral areas of the Hebei Plain in that sequence, with Zone covering only the southwest and northeast corners, characterized by the lowest yield and highest variation. Model analysis showed that Y was significantly correlated with F1, F3, F4, and F5 ($R^2 = 0.685$, $P < 0.01$), and these factors explained 68.5% of Y, where irrigation (F3) was the most important factor, explaining 37.4%, and fertilizer (F1) explained 21.7%. Annual rainfall (F4 and F5 together) explained only 9.4% of the whole model result, indicating a minor effect of annual rainfall on the spatial distribution of winter wheat production in Hebei Province. Pesticide (F2) was not factored into the Y regression model, showing that pesticide use had no significant effect on winter wheat production, underscoring that plant diseases and pests occurred randomly with no regional tendency. Regression analysis on winter wheat yield and the ratio of winter wheat area to total cropped area (F6) showed that F6 coincided with winter wheat yield among different counties ($R^2 = 0.409$, $P < 0.05$). Only a few counties in the far east of the low plain close to the coast belonging to Zone had the lowest winter wheat yield but abnormally high F6. The results showed that winter wheat production was basically proper under the existing management mode. However, under severe water shortage conditions, the abnormally high F6 values with low yield spots needed careful examination to ensure a healthy and sustainable high-efficiency cropping system. Nevertheless, in this study, only 68.5% of the production variables were explored, implying that other factors not accounted for in the analysis also affected winter wheat production.

Keywords: Winter wheat; Spatial structure; Yield variation; Irrigation; Control factor; Hebei Province

Introduction

The North China Plain is one of China' s three major concentrated wheat production regions. Located in the heart of this plain, Hebei Province is an important traditional agricultural province. In recent years, wheat planting area has remained at 2.4 million hectares, with total output reaching 12 million tons, accounting for 10% of the national total in both area and production, making its wheat production significant for national food security [1]. Numerous studies have shown that under irrigated conditions, winter wheat production in the Huang-Huai-Hai region is characterized by high and stable yields with good quality [2-6]. However, this region lies in a continental monsoon climate zone with large spatiotemporal variation in climatic elements. Average annual precipitation of 450–550 mm cannot meet the water requirements of wheat growth, making wheat production heavily dependent on irrigation. Long-term groundwater extraction for irrigation has created the largest groundwater funnel area in the country [7]. Against the backdrop of climate change and water shortage, clarifying the spatial pattern of winter wheat production and its control factors is crucial for rational layout and production planning, and for sustainable food production and resource utilization in this region.

Xu Zhiyu et al. [8] used a grain production gravity center model and an analysis model of internal and external driving factors to analyze changes in national wheat production patterns over the past 30 years, finding that sowing area was the key driving element, with total population, effective irrigated area, total agricultural machinery power, and fertilizer input all having significant impacts. Mo Xingguo et al. [9] used a process-based coupled model of soil-vegetation-atmosphere systems and crop growth to analyze spatiotemporal distribution and driving mechanisms of winter wheat yield in the Huang-Huai-Hai region, revealing obvious spatial differentiation closely related to irrigation conditions and soil. Wang Yong [10] used a comparative advantage model combined with spatial econometrics to analyze evolution characteristics of wheat distribution in the region, noting that wheat yield clearly concentrated in central-eastern Henan and northern Anhui, with effective irrigation area proportion, per capita cultivated land, tractor power per unit area, and rural labor non-agricultural employment proportion positively affecting wheat yield. Wang Qian et al. [11] combined GIS with spatial correlation analysis, showing that in recent years, sowing area and pesticide use have become more important for grain yield, while effective irrigated area, fertilizer use, agricultural machinery power, and drainage and irrigation machinery power remained major factors. Zhang Lulu et al. [12] used a spatial autocorrelation model to analyze nearly 20 years of data from 136 counties in Hebei, finding that effective irrigation area guarantee rate, pesticide use per unit area, labor input per unit, and fertilizer use per unit area were the main factors affecting grain yield pattern changes. Bai Lijia et al. [13] found that effective irrigation area, labor input per unit area, and grain purchase price index were the most important factors affecting grain yield per unit area patterns. Wang Yuqian [14] used GIS and regression analysis to analyze spatiotemporal patterns and influencing factors of grain crop input-output in Hebei over 20 years, showing that Baoding had the highest average grain yield while Qinhuangdao had the lowest, with a basic pattern of high yields in central-southern areas and low yields in northern areas, where fertilizer use, grain sowing area, effective irrigation area, and total agricultural machinery power significantly affected grain yield. Liu Zhongpei et al. [15] studied the relationship between fertilizer use and grain yield over nearly 30 years in the Shijiazhuang Plain region of Hebei, a high-yield, major grain-producing area, indicating that wheat-maize yields increased 2.18-fold with increasing fertilizer application.

These studies provide a general understanding of the overall grain and winter wheat production spatial patterns and control factors in Hebei and the Huang-Huai-Hai region. However, research specifically addressing the production pattern and control factors of winter wheat in Hebei, which faces enormous challenges, remains scarce. Therefore, this paper takes 101 counties in Hebei' s major winter wheat production area as regional units, using multivariate statistical analysis methods including cluster analysis, factor analysis, and regression analysis to dissect the regional patterns and control factor mechanisms of winter wheat production in Hebei, analyze the rationality and existing problems of the current layout, and provide a basis for efficient production and scientific planning management of winter wheat.

1. Materials and Methods

1.1 Data Sources

Winter wheat yield per unit area is affected by both natural and human factors. Temperature, precipitation, and sunlight are natural factors primarily determined by regional geographic characteristics, while production inputs such as variety, irrigation, and fertilizer are mainly influenced by human activities [16]. Over the past decade, northern China has experienced a drying climate trend, but increased production inputs have mitigated the negative impacts of climate change on winter wheat production to some extent [17]. Variety renewal has increased winter wheat yield by more than 20%, making it one of the major input factors [18-19]. However, due to lack of statistical data and because this study focuses on regional distribution patterns, we assumed that variety replacement was approximately synchronized across regions and temporarily ignored the differential effects of variety improvement among counties.

Therefore, this study selected fertilizer use, irrigation area proportion, pesticide use, and annual precipitation as agricultural factors affecting winter wheat yield. The analysis used annual county-level data from 2004-2013 on crop fertilizer use (pure content), crop pesticide use, effective irrigated area, winter wheat sowing area, and corresponding annual precipitation. County agricultural data were extracted from the *Hebei Rural Statistical Yearbook* [20], and annual precipitation (AR) was obtained from standard meteorological data provided by the Meteorological Data Sharing Service Network.

To further eliminate interference caused by differences in total cultivated land area, all county-level agricultural factor values (except winter wheat yield per unit area) were divided by total crop sowing area to obtain winter wheat sowing area proportion (ARW), irrigation area proportion (AI), fertilizer use per unit area (XF), and pesticide use per unit area (DDT).

Winter wheat production in Hebei is mainly concentrated in the central-southern plain region, with minimal planting in northern Zhangjiakou and Chengde areas. To eliminate statistical interference from low winter wheat planting proportions, this study selected 101 counties where the winter wheat sowing area proportion exceeded 20% of total crop sowing area as the basic research units, as shown in Figure 1 [Figure 1: see original paper].

1.2 Variation Characteristics

This study used the coefficient of variation and confidence intervals to reflect variability in winter wheat yield and its related factors: fertilizer use, irrigation area proportion, pesticide use, and annual precipitation. The coefficient of variation ( ) is the ratio of standard deviation to mean [21], as shown in Equation (1).

Where represents the coefficient of variation for a given factor, x represents the variable mean, xi represents the ith actual value, and n represents the data duration. A larger coefficient of variation indicates greater variability in the variable.

Additionally, the upper and lower limits of the 95% confidence interval and the mean were used to represent variable variation magnitude. Larger differences between upper and lower limits indicate greater variability.

1.3 Analytical Methods

1.3.1 Regional Division of Winter Wheat Yield Using Cluster Analysis Cluster analysis is a process of grouping a set of physical or abstract objects into multiple classes based on attribute indicators, with the goal of classifying data based on similarity [22]. Hierarchical cluster analysis, with clear steps and intuitive results, is widely used in various regional division studies [23–24]. The basic principle is to first treat n samples as n classes, then define similarity indices between samples and between classes, merge the two most similar classes into a new class, calculate distances between the new class and other existing classes, and repeat this process until all samples are merged into one class [25].

This study used the maximum, minimum, and mean values of winter wheat yield per unit area as classification indicators, Euclidean distance between samples [see Equation (2)] as the similarity index, and the sum of squared deviations method as the clustering criterion to obtain the final classification. In the equation, Dij represents the similarity coefficient of yield per unit area between county i and county j; x ik represents the standardized value of indicator k for county i; x jk represents the standardized value of indicator k for county j; and n represents the total number of indicators for the study counties.

1.3.2 Factor Analysis of Yield Regional Difference Control Factors Factor analysis is a statistical technique for extracting common factors from variable groups. By studying relationships among numerous variables, it expresses shared information among measured variables as a series of independent latent variables, i.e., common factors [26–27].

To eliminate statistical interference from low winter wheat planting proportions, this study selected only those counties with winter wheat sowing area proportion exceeding 20%. For n samples with p observed variables each, the original variables are represented by X = (x1, x2, ···, xp), and common factors by F(F1, F2, ···, Fm) (where m < p). The factor analysis model [28] can be expressed as:

Where F1, F2, ···, Fm are common factors that are independent and unobservable, representing information 隐含 in each original observed variable; aij are factor loadings, where larger absolute values indicate greater dependence of Xi on Fj, meaning Fj contains more information about Xi; and represents the specific factor, accounting for variable variation caused by influences other than common factors.

This study selected fertilizer use, irrigation area proportion, sowing area proportion, annual precipitation, pesticide use, and winter wheat yield in each production zone, constructing indicator systems using their means, 95% confidence interval upper and lower limits, and maximum and minimum values during the analysis period (2004–2013). Factor analysis was used to extract principal components, with varimax rotation applied to the factor loading matrix to facilitate interpretation. Finally, linear relationships between winter wheat yield and each factor were established based on the principal component score coefficient matrix.

1.3.3 Stepwise Regression Analysis Between Winter Wheat Yield and Control Factors Based on the comprehensive factor model from the factor analysis, actual values were introduced to calculate county-level scores for the winter wheat yield factor and each element factor [29]. Using the yield factor as the dependent variable and each element factor as independent variables, stepwise regression analysis [30] was performed to establish a relationship model between comprehensive winter wheat yield variation and significantly influential control factors.

1.4 Software Environment

Data processing and charting were completed using Microsoft Excel 2010, data analysis was performed using SPSS 19.0, and spatial distribution maps of winter wheat production in Hebei were produced using ArcGIS 10.0.

2. Results

2.1 Spatial Pattern of Winter Wheat Production in Hebei Province

Using hierarchical cluster analysis for regional division of winter wheat yield, the dendrogram results combined with inter-class distance differences and regional characteristics of winter wheat production led to the division of Hebei' s major winter wheat production area into four zones. Zone is mainly distributed in counties around Shijiazhuang City, with other zones radiating outward from Zone (Figure 1 [Figure 1: see original paper]).

Winter wheat production is concentrated in Zones – , accounting for 83% of the province' s total winter wheat output, with a decreasing trend from Zone to Zone . Yield variation shows a regular pattern of decreasing with increasing average yield, with Zone being most stable and Zone having the largest variation.

Univariate ANOVA with LSD multiple comparison tests showed significant differences in winter wheat yield levels among zones ($P < 0.01$). Except for the non-significant difference in yield variation coefficients between Zones and ($P > 0.05$), differences in variation coefficients among other zones were all significant ($P < 0.01$).

In summary, the high-yield Zone is located in the central area of the piedmont plain of the Taihang Mountains, mainly comprising counties around Shijiazhuang, with flat terrain, fertile soil, and well-developed agricultural infrastructure. The moderately high-yield Zone surrounds Zone in the plain area. The lower-yield Zone is distributed in the western Taihang Mountain area and the northeastern part of the North China Plain. The low-yield and unstable Zone is distributed in the southwestern and northeastern corners of Hebei Province.

2.2 Factor Analysis of Yield and Control Factors

2.2.1 Factor Analysis of Winter Wheat Yield and Control Factors Factor analysis was conducted on an indicator system comprising mean values and variation indicators (including mean, 95% confidence interval lower limit, 95% confidence interval upper limit, minimum, and maximum) for selected factors: fertilizer use, irrigation area proportion, sowing area proportion, annual precipitation, and pesticide use. Based on the principle of eigenvalues greater than 1 and cumulative variance contribution rate greater than 85%, five principal components were extracted with a cumulative variance contribution rate of 95.022% (Table 2).

Examination of the factor loading matrix (Table 3) shows that Principal Component 1 primarily contains information on fertilizer use, thus termed the fertilizer factor (F1), with a variance contribution rate of 41.219%. Similarly, Principal Component 2 is termed the pesticide factor (F2) with 22.248% contribution, Principal Component 3 is the irrigation area factor (F3) with 15.650%, Principal Component 4 (with highest loadings for mean annual precipitation, 95% confidence interval upper limit, and maximum value) is the annual precipitation factor (F4) with 10.686%, and Principal Component 5 (with highest loadings for 95% confidence interval lower limit and minimum annual precipitation) is the minimum annual precipitation factor (F5) with 5.219% contribution. These variance contribution rates reflect each factor' s representation of information in the entire factor system, showing that fertilizer, pesticide, and irrigation factors are the most important in this indicator system.

Based on the component score coefficient matrix for winter wheat yield control factors (Table 4), linear relationships between principal components and factor indicators can be established. For example, the fertilizer factor F1 score can be expressed as Equation (4).

Additionally, factor analysis of the indicator system for winter wheat yield variation in Hebei from 2004-2013 yielded one comprehensive yield factor (Y) with a variance contribution rate of 95.269%, and its factor score [Equation (5)].

2.2.2 Stepwise Regression Analysis Between Winter Wheat Yield and Control Factors Using the winter wheat yield principal component score (Y) as the dependent variable and the comprehensive factor scores of production elements F1 (fertilizer), F2 (pesticide), F3 (irrigation), F4 (annual precipitation), and F5 (minimum annual precipitation) as independent variables, stepwise regression analysis yielded the regression equation [Equation (6)], with the pesticide factor (F2) removed due to non-significance.

Regression parameters (Table 5) show the equation has a determination coefficient $R^2 = 0.685$, indicating that fertilizer factor (F1), irrigation area factor (F3), annual precipitation factor (F4), and minimum annual precipitation factor (F5) together explain 68.5% of winter wheat yield and variation information. Among these, the irrigation factor (F3) is the most important, explaining 37.4% of yield variation, followed by fertilizer factor (21.7%), annual precipitation factor (7.9%), and minimum annual precipitation factor (1.5%). This also indicates that precipitation has a relatively small effect on the regional distribution of winter wheat in Hebei, likely masked by irrigation capacity and fertilization effects.

2.3 Regional Differences in Control Factors

2.3.1 Regional Differences in Irrigation Area Proportion Table 6 shows that average irrigation area proportions in all zones exceed 50%, with Zone having the highest and Zone the lowest, and significant differences among zones ($P < 0.01$). Variation degree is smallest in Zone and largest in Zone , with significant differences among zones ($P < 0.01$). Notably, counties with the highest irrigation area proportions in the province–Zhao County, Gaocheng, Zhengding, Shenze, Jinzhou–are all in Zone , with average irrigation area proportions above 95%. These patterns are consistent with average yield and variation trends (Table 1), demonstrating the important role of irrigation area proportion in the spatial layout and yield variation of winter wheat in Hebei.

2.3.2 Regional Differences in Fertilizer Use and Annual Precipitation Winter wheat fertilizer use ranges from 192.11 to 1,628.21 kg·hm ². Ranking by average fertilizer use: Zone > Zone > Zone > Zone . Ranking by coefficient of variation: Zone < Zone < Zone < Zone (Table 6), with significant differences in both average fertilizer use and variation coefficients among zones ($P < 0.01$). Counties with the highest fertilizer use are concentrated in Zone , where winter wheat yield and irrigation area proportion are also provincially high, indicating that fertilizer use aligns with regional distribution trends of winter wheat yield. Table 6 also shows no significant differences in annual precipitation variation among zones ($P > 0.05$), but significant differences in mean precipitation ($P < 0.05$), with Zone having the least and Zone the most, showing an increasing trend from Zone to Zone —opposite to the yield trend. This indicates that annual precipitation has minimal impact on regional yield differences, likely masked by irrigation and fertilization effects.

2.4 Winter Wheat Yield and Sowing Area Proportion

Table 7 shows the ranking of average sowing area proportion: Zone > Zone > Zone > Zone , with significant differences among zones ($P < 0.05$). The ranking of variation coefficients: Zone < Zone < Zone < Zone , but differences are not significant ($P > 0.05$).

The relationship between sowing area proportion and yield across zones (Figure 3 [Figure 3: see original paper]) shows a significant linear relationship ($R^2 = 0.141$, $P < 0.05$), indicating a trend where counties with lower yields have smaller sowing area proportions. However, Zone , with the lowest average yield and highest variation coefficient, shows relatively large sowing areas in low-yield counties such as Cang County, Huanghua City, Yanshan County, Mengcun, She County, and Haixing County. When these six outlier counties are removed, the linear relationship improves significantly, with a determination coefficient $R^2 = 0.409$ ($P < 0.05$).

3. Conclusions and Discussion

This study analyzed the spatial pattern and control factor mechanisms of winter wheat production in Hebei Province using 101 counties in the major production area as research units and employing mathematical statistical analysis methods. The main findings are as follows:

Spatial pattern of winter wheat production in Hebei: The major production area is concentrated in the central-southern plain region, showing an overall trend of decreasing yield from the high-yield center outward. High-yield areas are mainly concentrated in the plain region surrounding Shijiazhuang City, with good yield stability, large irrigation area rates, and high fertilizer use. Low-yield areas are mainly distributed in the peripheral regions of the central-southern plain, with high yield variability, small irrigation area rates, and low fertilizer use.

Control factors of the spatial pattern: Irrigation area and fertilizer use are the most important factors affecting the winter wheat spatial pattern, consistent with research results on Hebei' s grain spatial pattern by scholars [11–14]. Irrigation area is the primary factor affecting the production pattern and also an important yield factor, with irrigation area rates exceeding 95% in high-yield regions. Fertilizer use plays a secondary role in spatial distribution, while annual precipitation has a smaller impact, indirectly demonstrating that irrigation compensates for insufficient or regionally variable precipitation. Additionally, pesticide use has no significant effect on spatial pattern distribution, indicating no clear regional trends in pest and disease occurrence and control.

This study also found that several counties—Haixing, Cang County, Huanghua City, Mengcun, Yanshan County, and She County—located in the northeastern low plain or coastal areas have low wheat yields but high sowing areas, suggesting potentially abnormal sowing area proportions that warrant attention. In other counties, winter wheat sowing area aligns well with yield, with high-yield counties having high production stability and planting proportions, indicating that the current provincial winter wheat layout is basically rational.

Using yield and its variability to analyze Hebei' s winter wheat production pattern, the model based on irrigation area, fertilizer use, and annual precipitation explains 68.5% of yield variation information, reflecting reasonable patterns of spatial structure and control factors. However, this also indicates that a large proportion of information remains unexplained, and some important factors such as variety were not considered. Under climate change, meteorological elements such as temperature and sunshine may also affect local winter wheat production patterns. This study assumed that spatial changes in variety and meteorological elements were random or synchronized over time, ignoring regional differences in variety replacement and temperature changes. Whether these factors can be ignored and how large their impacts are will be addressed in future research by incorporating these factors and their temporal changes, extending the study period, and conducting more comprehensive analyses of control factors to make results more reliable and scientific.

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Note: Figure translations are in progress. See original paper for figures.