

# Article Spatiotemporal Evolution and Influencing Factors of Soybean Production in Heilongjiang Province, China

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Abstract: Heilongjiang Province, as the largest production and supply base for high-quality soybeans in China, plays a vital role in optimizing the layout of soybean production and promoting the revitalization of the soybean industry. Soybean yield is used as a key indicator of soybean production. This study integrated soybean yield data from agricultural reclamation systems and local authorities. A variety of statistical analysis methods, such as barycenter analysis, the Mann-Kendall test, the space-time cube, and grey relational analysis, were used to research the spatiotemporal evolution and influencing factors of soybean production in Heilongjiang Province from 2011 to 2021. This paper revealed the spatiotemporal evolution mechanism and explored the reasons for the differences in the effects of influencing factors. The results were as follows. (1) During the period between 2011 and 2021, the center of gravity of county-level soybean yield in Heilongjiang Province moved towards the northwest over a distance of 16.82 km. The soybean yield in the province experienced a mutation in approximately 2018, from a downward trend to an upward trend. (2) The spatiotemporal hot spots of county-level soybean yield in Heilongjiang Province were concentrated along the line from Hailun to Aihui. The types of hot spots included consecutive hot spots, intensifying hot spots, sporadic hot spots, and new hot spots. (3) The spatiotemporal agglomeration patterns of county-level soybean yield in Heilongjiang Province included only high-high clusters, only low-low clusters, only high-low outliers and multiple types. (4) The temporal changes in soybean yield in various counties of Heilongjiang Province had obvious regional characteristics. (5) Socioeconomic factors had aftereffects on soybean planting decisions. (6) Sunlight hours, the price ratio of local soybeans to local maize, average temperature, the number of soybean patents, the price ratio of imported soybeans to local soybeans, soybean cultivation income, local soybean prices, and the number of newly established soybean enterprises were primary influencing factors. Precipitation and soybean import volume were secondary influencing factors. The income difference between maize and soybeans, crops-hitting disaster area, and maize yield were general influencing factors. This study aims to offer new pathways for alleviating the structural contradiction between soybean supply and demand and to provide a reference for the formulation of national soybean industry policies and food security strategies.

**Keywords:** soybean production; space–time cube; spatiotemporal evolution; influencing factors; Heilongjiang Province

## 1. Introduction

Soybeans serve as both a plant protein source and an herbaceous oil crop, playing an important role in human life, economic development, and food security [1]. China has a long-standing history of soybean production. With the rapid development of soybean cultivation in modern Northeast China, soybeans have become a landmark product in its agricultural economic history. Soybean export trade in Northeast China once occupied a



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**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). core position globally [2], especially in the first 30 years of the 20th century [3]. Subsequently, factors such as the rise of soybean production in the United States, the promotion of fertilizers in Japan, the Great Depression, and the outbreak of the Second World War led to the gradual decline and eventual collapse of the soybean industry in Northeast China [4]. After the establishment of the People's Republic of China, grain production experienced rapid growth. However, soybean cultivation has been caught in a state of relative stagnation at a low level [5]. With the increase in population size and the expansion of arable land in Northeast China, the soybean cultivation zone continues to shift northwards [6]. Heilongjiang Province has become the largest soybean production area in China.

Since the 1990s, with the development of the social economy, the increase in national income and the upgrading of the consumption structure, there has been a strong demand for meat, eggs and dairy products. As a result, soybean consumption has been steadily increasing [7]. China implemented the soybean import liberalization policy in 1996, and the country became the world's largest soybean importer by 1999. Under the multiple impacts of import shocks, resource constraints and declining returns, domestic soybean market competitiveness has been weakened [8], and soybean production in Northeast China has also faced challenges. In 2022, China produced 20.28 million tons of soybeans and imported 91.08 million tons of soybeans. The external dependence of soybean consumption is as high as 81.79%, which seriously affects the security of China's soybean industry [9]. To ensure effective supply and increase farmers' income, structural reform of the agricultural supply side has emerged. One of the most important aspects is to adjust the planting structure in order to address the structural contradiction of insufficient soybean supply [10]. Heilongjiang Province plays a vital role in optimizing the layout of soybean production and promoting the revitalization of the soybean industry. Therefore, analyzing the spatiotemporal evolution and influencing factors of soybean production in Heilongjiang Province in recent years is not only an important academic objective but also an urgent need.

As an important research direction in agricultural geography, the spatiotemporal evolution and influencing factors of soybean production have been extensively discussed by scholars. Research on the spatiotemporal evolution of soybean production has been performed in the United States [11], Brazil [12], Argentina [13], China [14] and other main producers of soybeans. The Midwest of the United States is the most important soybean production region in the world, forming a well-known soybean-maize belt [15]. Soybean production in South America has grown significantly. The soybean planting area in Brazil has expanded from the southern region to the central-western and northern regions [16], with the fastest growth occurring in the Amazon region from 2000 to 2019. Centered around the provinces of Buenos Aires, Cordoba, and Santa Fe, Argentina's main soybean production areas have continuously expanded southwards [17]. In China, the production advantage of the Northeast Plain has been continuously strengthened, while that of the Huang-Huai-Hai Plain has declined. The northwest interior region, Sichuan Basin, Yunnan-Guizhou Plateau, and Middle-Lower Yangtze Plain have become new areas of growth [18].

Various factors affect soybean production, which can be broadly divided into two categories: factors affecting soybean unit-yield level and factors affecting soybean planting area. Factors affecting soybean unit-yield level include climatic conditions [19], natural disasters [20], crop varieties [21], cultivation methods [22], land quality [23], etc. The soybean planting area is mainly constrained by the quantity of arable land resources and farmers' planting intentions. In terms of arable land resources, the yield per unit area of soybeans is lower than that of high-yield grain crops such as rice and maize, and more cultivated land is needed for unit soybean output [24]. Consequently, soybean production is significantly restricted by arable land resources. In terms of planting intentions, operating income is the main driving force of farmers' planting decisions [25]. Factors such as production costs [26], crop yields [27], planting subsidies [28], market conditions [29], international trade [30], competitive crops [31], technology research [32], industrial development [33],

and business models [34] will all have an impact on farmers' operating income. In addition, the willingness to plant of individual farmers is also limited by non-economic factors such as planting habits [35], education level [36], and policy orientation [37], etc.

However, there are still some shortcomings in the current literature on the spatiotemporal evolution and influencing factors of soybean production. (1) When exploring the spatiotemporal evolution of soybean production, scholars generally conduct period-byperiod spatial analysis based on spatial panel data and then integrate spatial changes in time series. The essence of this approach is still traditional spatial analysis, without space-time dimension integration. (2) Relevant research often focuses on the national or regional level, with insufficient discussion about Heilongjiang Province. However, soybean production also exhibits significant differences among counties in Heilongjiang Province. (3) The Heilongjiang land reclamation system boasts a state-owned farm group that possesses the largest arable land area, the highest level of modernization, and the strongest comprehensive production capacity in China, occupying a special position in Heilongjiang agricultural production. Due to the transformation of the Heilongjiang Province Farms and Land Reclamation Administration into an agricultural reclamation enterprise group in 2020, agricultural data originally belonging to the Heilongjiang Province Farms and Land Reclamation Administration were merged into local authorities, resulting in an inconsistent statistical caliber of county-level soybean yield data for Heilongjiang Province during the research period.

On this basis, this study focused on soybean yield, integrated data from agricultural reclamation systems and local authorities, and used methods such as barycenter analysis, the Mann–Kendall test, the space–time cube, and grey relational analysis to research the spatiotemporal evolution and influencing factors of soybean production in Heilongjiang Province from 2011 to 2021. The space–time cube model integrates the spatial, temporal and attribute information of geographical phenomena, which can effectively detect the spatiotemporal distribution patterns and rules of soybean production in Heilongjiang Province combined with barycenter analysis. The Mann–Kendall test and grey relational analysis are simple to calculate and do not require samples to follow a certain distribution. The former is not affected by a few outliers, while the latter has no special requirements for sample size.

This study revealed the spatiotemporal evolution mechanism of soybean production in Heilongjiang Province, explored the reasons for the differences in the effects of influencing factors, and proposed suggestions for the development of the soybean industry. Based on Heilongjiang Province, this paper aims to optimize the layout of soybean production, promote the revitalization of the soybean industry, offer new pathways for alleviating the structural contradiction between soybean supply and demand, and provide references for the formulation of national soybean industry policies and food security strategies.

#### 2. Materials

#### 2.1. Study Area

Heilongjiang Province is located in Northeast China, and belongs to one of the world's three representative black soil belts (Figure 1). It is the largest production and supply base for high-quality soybeans in China, known as "the hometown of soybeans". Heilongjiang Province has advantageous conditions for soybean cultivation, including extensive arable land, fertile soil with a loose texture, simultaneous heat and precipitation, and abundant sunlight. In 2022, the soybean planting area in Heilongjiang Province was 4.93 million hm<sup>2</sup>, accounting for 48.1% of the total soybean planting area in China. Its soybean yield was 9.53 million tons, accounting for 47% of China's total soybean yield. Soybean production in Heilongjiang Province plays a crucial role in ensuring national food security, especially in terms of soybean supply. Thus, Heilongjiang Province is a typical and representative area for research.



Figure 1. Overview of Heilongjiang Province and its location in China.

## 2.2. Data and Processing

## 2.2.1. Administrative Division Data

The administrative division data of Heilongjiang Province were obtained from the basic geographic information database maintained by the Ministry of Natural Resources of China (https://www.webmap.cn/ (accessed on 18 April 2023)). Due to the district-to-county reform, the administrative divisions of Yichun City underwent significant adjustments in 2019. Taking into account the comparability of statistical data, the municipal districts of each prefecture-level city in Heilongjiang Province were integrated, and then the county-level administrative divisions were adjusted to the boundary state of 2018. This study involved 75 county-level administrative units in Heilongjiang Province.

## 2.2.2. Soybean Yield Data

Soybean yield data at the county level were sourced from the Heilongjiang Statistical Yearbook, the Statistical Yearbook of Heilongjiang State Farms, statistical yearbooks of cities, and national economic and social development statistical bulletins issued by county governments. To solve the problem of inconsistent statistical calibers of soybean yield data in each county of Heilongjiang Province, the soybean yield data of farms affiliated with the agricultural reclamation system from 2011 to 2018 were integrated into the county-level space. By adding these farm data to the original county-level data, county-level soybean yield data without the impact of statistical caliber changes were obtained.

#### 2.2.3. Physical Geographic and Socioeconomic Data

Relevant data came from the Heilongjiang Statistical Yearbook, China Statistical Yearbook, China Rural Statistical Yearbook, Compilation of National Cost and Revenue of Agricultural Products, and some government and enterprise websites, such as the Finance Bureau of Heilongjiang Province (https://czt.hlj.gov.cn/czt/index.shtml (accessed on 1 June 2023)), Patenthub (https://www.patenthub.cn/ (accessed on 1 June 2023)), and Qichacha (https://www.qcc.com/ (accessed on 1 June 2023)).

#### 3. Methods

## 3.1. Barycenter Analysis

Barycenter analysis was used to detect the spatiotemporal evolution path of the soybean production barycenter in Heilongjiang Province [38,39]. Assuming that one region is composed of *n* sub-regions, the coordinate of the barycenter of sub-region *i* is  $(X_i, Y_i)$ , and  $M_i$  is the "weight" of sub-region *i* for the soybean yield attribute, then the regional barycenter coordinate (X', Y') of this attribute is defined as:

$$X' = \frac{\sum_{i=1}^{n} M_i X_i}{\sum_{i=1}^{n} M_i} \quad Y' = \frac{\sum_{i=1}^{n} M_i Y_i}{\sum_{i=1}^{n} M_i} \tag{1}$$

where *n* is the number of county-level administrative units in Heilongjiang Province, with a value in this paper of 75;  $(X_i, Y_i)$  is taken as the coordinates of the centroid of county *i* and  $M_i$  is the soybean yield in county *i*.

#### 3.2. Mann-Kendall Test

The Mann–Kendall test is a nonparametric statistical test method that was originally proposed by Mann [40] and Kendall [41] and has been continuously improved by other scholars [42].

## 3.2.1. Mann-Kendall Trend Test

The Mann–Kendall trend test was used to determine the changing trend of soybean yield in Heilongjiang Province. For the soybean yield time series  $x (x_1, x_2, ..., x_n)$ , the Mann–Kendall trend test statistic *S* is as follows [43]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i)$$
(2)

where  $x_i$  and  $x_j$  are the *i*-th and *j*-th data values of the time series **x**, respectively; *n* is the sample size and sgn(\*) is the sign function. When  $n \ge 8$ , the statistic *S* approximately follows a normal distribution, with a mean of 0 and a variance as follows:

$$Var(S) = \frac{n(n-1)(2n+5)}{18}$$
(3)

The standardized test statistic  $Z_c$  is computed as follows:

$$Z_{c} = \begin{cases} \frac{(S-1)}{\sqrt{\operatorname{Var}(S)}} & S > 0\\ 0 & S = 0\\ \frac{(S+1)}{\sqrt{\operatorname{Var}(S)}} & S < 0 \end{cases}$$
(4)

The size of the trend can be expressed using the Kendall inclination  $\beta$ , which is calculated as follows:

$$\beta = \text{Median}(\frac{x_i - x_j}{i - j}) \tag{5}$$

where 1 < j < i < n and Median(\*) is the median function. When  $\beta > 0$ , it indicates that the soybean yield time series shows an upward trend; when  $\beta < 0$ , it indicates that the soybean yield time series shows a downward trend. When the absolute value of  $Z_c$  is greater than or equal to 1.65, 1.96, and 2.58, the significance test has passed at the 90%, 95%, and 99% confidence levels, respectively [44].

## 3.2.2. Mann-Kendall Mutation Test

The Mann–Kendall mutation test was used to determine the time point of soybean yield mutation in Heilongjiang Province. For the soybean yield time series  $x (x_1, x_2, ..., x_n)$ , construct an order column:

$$S_k = \sum_{i=1}^k r_i \ (k = 2, 3, \cdots, n)$$
 (6)

where:

$$r_{i} = \begin{cases} 1 & x_{i} > x_{j} \\ 0 & x_{i} \le x_{j} \end{cases} (j = 1, 2, \cdots, i)$$
(7)

 $S_k$  is the cumulative number of times the value of *i* at moment *i* is greater than the number of values at time *j*. Under the assumption of random independence of time series, the statistic is defined as follows:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{\operatorname{Var}(S_k)}} \quad (k = 1, 2, \cdots, n)$$
(8)

where  $UF_1 = 0$ ;  $E(S_k)$  and  $Var(S_k)$  are the mean and variance of  $S_k$ , respectively. When  $x_1, x_2, ..., x_n$  are independent of each other and have the same continuous distribution, they can be approximately expressed as [43]:

$$E(S_k) = \frac{k(k-1)}{4} (2 \le k \le n)$$
  

$$Var(S_k) = \frac{k(k-1)(2k+5)}{72} (2 \le k \le n)$$
(9)

The above procedure can be repeated by  $x_n, x_{n-1}, ..., x_1$ , and let  $UB_k = -UF_k$  (k = n, n-1, ..., 1), where  $UB_1 = 0$ . Given the significance level  $\alpha = 0.05$ , the critical value  $U_{0.05}$  is  $\pm 1.96$ . Then, the curves of  $UF_k$  and  $UB_k$  and the straight line of the critical value can be drawn.  $UF_k > 0$  indicates an upward trend;  $UF_k < 0$  indicates a downward trend.  $UF_k > 1.96$  suggests a significant upward trend;  $UF_k < -1.96$  suggests a significant downward trend. If there exist intersecting points of the two curves of  $UF_k$  and  $UB_k$  and the value of the intersecting points is between the critical values, the moment corresponding to the intersection may be the moment when the mutation starts [45].

## 3.3. Spatiotemporal Data Mining Based on the Space–Time Cube

#### 3.3.1. Space–Time Cube

The space–time cube, as a three-dimensional data model, was first proposed by Hägerstrand [46]. The X-axis and Y-axis represent the spatial location of geographic objects, while the *T*-axis represents time, with the bottom layer indicating the start time and the top layer indicating the most recent time (Figure 2). Each bin in the space–time cube has a location ID, a time step ID, and an attribute value. Bins with the same location ID form a bin time series, while bins with the same time step ID form a time slice [47]. Each bin corresponds to a separate attribute value. Based on the space–time cube model, emerging hot spot analysis, local outlier analysis, and time series clustering can be performed. The description and usage of these methods can be obtained online (https://pro.arcgis.com (accessed on 1 June 2023)), so only a brief introduction in this paper. In this study, the location ID of a bin represents the spatial location of a county-level administrative unit in Heilongjiang Province, the time step ID represents a year, and the attribute value represents the soybean yield of the county-level administrative unit.



Figure 2. Space-time cube model.

## 3.3.2. Emerging Hot Spot Analysis

Emerging hot spot analysis was used to depict the spatiotemporal distribution pattern of soybean production in Heilongjiang Province. The basic idea is to first conduct traditional hot spot analysis based on the soybean yield space–time cube, obtain the Getis–Ord Gi\* statistic for each bin in each time slice [48], and then use the Mann–Kendall trend test to evaluate the changing trend of hot and cold spots for each bin time series. Its neighborhood definition takes into account the space–time dimension. A bin is considered a neighborhood if its centroid falls within the space neighborhood range and its time interval is within a specified time neighborhood step. The results of the emerging hotspot analysis are divided into 17 categories, namely, new, consecutive, intensifying, persistent, diminishing, sporadic, oscillating, and historical hot and cold spots, as well as no pattern detected [49].

#### 3.3.3. Local Outlier Analysis

Local outlier analysis was used to reveal significant clusters and outliers in soybean production in Heilongjiang Province, which is the spatiotemporal realization of the local Moran's index [50]. Its neighborhood definition is the same as that in emerging hot spot analysis. The results of the local outlier analysis are divided into 6 categories, namely, only high-high cluster, only high-low outlier, only low-high outlier, only low-low cluster, multiple types, and never significant [51].

## 3.3.4. Time Series Clustering

Time series clustering was used to identify counties with the most similar time series characteristics in the soybean yield space–time cube and partition them into distinct clusters. In this study, the profile feature that tends to increase or decrease simultaneously is selected, and the k-medoids algorithm is used to cluster soybean yield data. The optimal number of clusters is obtained by the pseudo-F statistic [52], which is a ratio of between-cluster variance to within-cluster variance. The larger the value, the more effective the number of clusters. The formula for calculating the pseudo-F statistic is as follows [53]:

$$F = \frac{\left(\frac{R^2}{m_c - 1}\right)}{\left(\frac{1 - R^2}{m - m_c}\right)} \tag{10}$$

where  $R^2$  is defined as follows:

$$R^{2} = \frac{SST - SSE}{SST}$$

$$SST = \sum_{i=1}^{m_{c}} \sum_{j=1}^{m_{i}} \sum_{k=1}^{m_{v}} \left( V_{ij}^{k} - \overline{V^{k}} \right)^{2}$$

$$SSE = \sum_{i=1}^{m_{c}} \sum_{j=1}^{m_{i}} \sum_{k=1}^{m_{v}} \left( V_{ij}^{k} - \overline{V^{k}_{i}} \right)^{2}$$
(11)

where *m* is the number of features;  $m_i$  is the number of features in cluster *i*;  $m_c$  is the number of clusters;  $m_v$  is the number of variables used to cluster features;  $V_{ij}^k$  is the value of the *k*-th variable of the *j*-th feature in the *i*-th cluster;  $\overline{V^k}$  is the mean value of the *k*-th variable and  $\overline{V_i^k}$  is the mean value of the *k*-th variable in cluster *i*.

#### 3.4. Grey Relational Analysis

Grey relational analysis can identify the dominant factors among the influencing factors of soybean production in Heilongjiang Province [54]. The core idea is to determine the closeness of the relationship based on the similarity of the geometric shapes of the sequence curves. The calculation steps are as follows:

- Soybean yield in Heilongjiang Province was used as the reference sequence, and influencing factors were used as the comparability sequences. The raw data are forward-processed based on the correlation relationship between each comparability sequence and the reference sequence.
- 2. To enhance the comparability between sequences, the reference sequence and the comparability sequences can be transformed into dimensionless forms by average-value processing. Average-value processing divides the elements in each sequence by the average value of the corresponding sequence.
- 3. The grey relational coefficient of the corresponding elements between each comparability sequence and the reference sequence is calculated. The calculation formula is as follows [55]:

$$e_{0i}(t) = \frac{\min_{i} \left( \min_{t} |x_{0}(t) - x_{i}(t)| \right) + \rho \max_{i} \left( \max_{t} |x_{0}(t) - x_{i}(t)| \right)}{|x_{0}(t) - x_{i}(t)| + \rho \max_{i} \left( \max_{t} |x_{0}(t) - x_{i}(t)| \right)}$$

$$i = 1, 2, \cdots, 13; \ t = 1, 2, \cdots, 11$$
(12)

where  $x_0(t)$  is the *t*-th sample value of the reference sequence after dimensionless transformation;  $x_i(t)$  is the *t*-th sample value of the *i*-th comparability sequence after dimensionless transformation;  $e_{0i}(t)$  is the grey relational coefficient between  $x_0(t)$  and  $x_i(t)$  and  $\rho$  is the distinguished coefficient. In general,  $\rho$  is equal to 0.5 because it offers a moderate distinguishing effect and stability.

4. Grey relational grade is defined as the numerical measure of similarity between two sequences, such as the reference sequence and the comparability sequence. The grey relational grade between each comparability sequence and the reference sequence is calculated based on the grey correlation coefficient. The calculation formula is as follows:

$$e_{0i} = \frac{\sum_{t=1}^{11} e_{0i}(t)}{11}$$
(13)

where  $e_{0i}$  is the grey relational grade between the reference sequence and the *i*-th comparability sequence. The grey relational grade between each comparability sequence and the reference sequence is calculated, and the influencing factors are ranked according to the numerical value of the grey relational grade. The higher the grey relational grade is, the greater the impact of this influencing factor on soybean yield in Heilongjiang Province, and vice versa.

## 4. Results

## 4.1. Spatiotemporal Evolution of Soybean Production in Heilongjiang Province 4.1.1. Overall Spatiotemporal Variation

Barycenter analysis was performed to reflect the spatiotemporal evolution of soybean production in Heilongjiang Province as a whole (Figure 3). From 2011 to 2021, the center of gravity of county-level soybean yield in Heilongjiang Province was mainly located in the northeast region of Suiling County, except for 2015 and 2017. Depending on the direction of movement, the trajectory of the center of gravity can be divided into four parts. (1) From 2011 to 2013, the center of gravity mainly moved to the southwest. (2) From 2013 to 2015, the center of gravity rapidly shifted northwards, from Suiling to Bei'an. (3) From 2015 to 2017, the center of gravity moved southeast to the Yichun municipal district. (4) From 2017 to 2021, the center of gravity continued to move westwards. In the past 11 years, the center of gravity of county-level soybean yield in Heilongjiang Province has shifted to the northwest by approximately 16.82 km, indicating a continuous improvement in the position of soybean production in northwestern Heilongjiang Province.



**Figure 3.** Path of the center of gravity of county-level soybean yield in Heilongjiang Province from 2011 to 2021.

The Mann–Kendall test was carried out on the soybean yield time series in Heilongjiang Province. In the Mann–Kendall trend test (Table 1), the inclination  $\beta$  was positive, indicating that the soybean yield in Heilongjiang Province has shown an upward trend in the past 11 years. However, this upward trend was not significant and did not pass the significance test at the 0.1 level. In the Mann–Kendall mutation test (Figure 4), the soybean yield in Heilongjiang Province showed a downward trend before 2017 and an upward trend after 2017, but these trends were not significant. There was an intersecting point between the  $UF_k$  curve and the  $UB_k$  curve, which passed the significance test at the 0.05 level. This indicated that the soybean yield in Heilongjiang Province experienced a

mutation in approximately 2018. Meanwhile, China launched the second round of the soybean revitalization plan in early 2019.

Table 1. The Mann–Kendall trend test of soybean yield in Heilongjiang Province from 2011 to 2021.



**Figure 4.** The Mann–Kendall mutation test of soybean yield in Heilongjiang Province from 2011 to 2021.

## 4.1.2. Spatiotemporal Model Construction

A space-time cube was constructed based on the soybean yield data of 75 county-level administrative units in Heilongjiang Province from 2011 to 2021. The spatial granularity of the space-time cube is at the county level, and the time step is 1 year. It contains 75 bin time series, each of which includes 11 time slices. Therefore, the soybean space-time cube is made up of 825 bins, and each bin corresponds to the soybean yield of a specific county in a specific year (Figure 5). According to the space-time cube, the interannual variation and spatiotemporal agglomeration of soybean yield in each county of Heilongjiang Province can be directly observed. Soybean yield data were divided into five categories according to the natural breakpoint method, where darker colors indicate higher soybean yields. The results showed that the soybean yield in the counties located in the northern part of Songnen Plain was relatively high, and an obvious soybean production agglomeration area was formed at the junction of Heihe, Qiqihar and Suihua. The counties in the middle of the Sanjiang Plain ranked second, among which Fujin and Baoqing had higher soybean yields. However, the average county-level soybean yield in the northern Songnen Plain was significantly higher than that in the Sanjiang Plain. In addition, the latter's production capacity distribution was more scattered, while interannual fluctuations correspondingly increased. The soybean yield in the southern counties of Heilongjiang Province was relatively low, and the production advantage was not prominent. Based on this, Heihe, Qiqihar, and Suihua have resource advantages for building a cross-administrative soybean industry cluster.



Figure 5. The county-level soybean yield space-time cube in Heilongjiang Province.

4.1.3. Spatiotemporal Hot Spot Distribution

Taking the space-time cube as input data, an emerging hot spot analysis was carried out on the soybean yield of 75 county-level administrative units in Heilongjiang Province (Figure 6). The spatiotemporal relationship among features was constructed by a fixed distance. The default spatial neighborhood distance is 107.76 km, which ensures that each county-level administrative unit has at least one neighboring element. The neighborhood time step is 1 year. Four types of hot spots were detected, but no cold spots were found. Hot spots were generally distributed in a north-south direction, concentrated along the line from Hailun to Aihui. Specifically, Hailun and Suiling are the southern boundaries of the hot spot area and were continuously displayed as hot spots during the study period, so they were identified as consecutive hot spots. Bei'an, Wudalianchi, Nenjiang, Aihui, Kedong and Keshan have also been identified as hot spots in the past 11 years, and the intensity of the hot spots has been continuously strengthening over time. As a result, they were recognized as intensifying hot spots. Sunwu and Baiquan were located on the edge of the hot spot area, where the hot spot pattern was unstable. They were only recognized as hot spots in some years, so they were classified as sporadic hot spots. In addition, Yi'an, located in the southwest of the hot spot area, was a county that was a statistically significant hot spot for the final time step and had never been a statistically significant hot spot before, so it was identified as a new hot spot. Overall, most of Heihe City, the northeastern part of Qiqihar City, and the northern part of Suihua City are the only concentrated and contiguous hot spots in Heilongjiang Province. They form the largest soybean production area in Heilongjiang Province, and this position continues to strengthen. This is also in line with the general trend of the center of gravity of soybean yield in Heilongjiang Province moving to the northwest.



**Figure 6.** Spatiotemporal hot spots of county-level soybean yield in Heilongjiang Province from 2011 to 2021.

#### 4.1.4. Spatiotemporal Agglomeration Pattern

Combining the space-time cube model and the local outlier analysis method, this study explored the spatiotemporal agglomeration pattern of county-level soybean yield in Heilongjiang Province from 2011 to 2021 (Figure 7). The definition of spatiotemporal relationships among features is the same as that employed for the emerging hot spot analysis. The counties with the only high-high cluster pattern were distributed in the northwestern part of Heilongjiang Province, and their regional scope highly overlapped with the spatiotemporal hot spots. This region is the largest soybean production area in Heilongjiang Province, and the soybean yields in nearby counties are relatively high, thereby demonstrating the only high-high cluster pattern. The counties showing the only low-low cluster pattern extended from Longjiang to Suibin, forming a ring-shaped distribution around the outer periphery of the counties with the only high-high cluster pattern. These counties include geographical units such as the southern part of the Songnen Plain, the Songhua River Valley, and the western part of the Sanjiang Plain. The distribution direction is consistent with the main streams of the Nen River and Songhua River. These areas have flat terrain, fertile soil, and favorable climate conditions, making them more economically advantageous for growing rice and maize than for growing soybeans. The soybean sown area and yield are relatively small, showing only a low-low cluster pattern. In this study, Linkou and Muling were identified as counties with the only high-low outlier pattern, and no county had the only low-high outlier pattern. Linkou and Muling are located in the hilly and shallow mountainous areas of southeastern Heilongjiang Province. Their unique natural ecological environment and regional microclimate are suitable for soybean growth. Boli, Yilan, and Fangzheng on the north side of these two counties exhibited the only low-low cluster pattern. In addition, the neighboring Jixi municipal district and Mudanjiang municipal district are mostly urbanized areas with limited land

resources and less soybean production. Maize is the main food crop in Jidong, Hailin, Ning'an and Dongning, and soybean production is not dominant. Therefore, the soybean yields in Linkou and Muling are higher than those of surrounding counties, showing the only high-low outlier pattern. The distribution of counties with the multi-type pattern was relatively scattered, involving Sunwu, Luobei, Huanan, and Shangzhi. These areas experienced significant fluctuations in soybean yields and exhibited different types of agglomeration patterns during the research period.



**Figure 7.** Spatiotemporal analysis of local outliers of county-level soybean yield in Heilongjiang Province from 2011 to 2021.

## 4.1.5. Time Series Analysis

Based on the space-time cube model, time series clustering was carried out on countylevel soybean yield in Heilongjiang Province from 2011 to 2021 (Figure 8). The clustering characteristic is the correlation of profiles, which means that counties with soybean yields that tend to increase or decrease proportionally at the same time will be clustered together. When the number of clusters was 2, the pseudo-F statistic was the largest, with a value of 75.63. As a result, the 75 county-level administrative units were grouped into two clusters. There were 35 counties in Cluster 1, mainly distributed in geographical units such as the Greater Khingan Mountains, the southern part of the Lesser Khingan Mountains, the southern part of the Songnen Plain, the Songhua River valley, and the mountainous and hilly areas of southeastern Heilongjiang Province. There were 40 counties in Cluster 2, mainly distributed in geographical units such as the northern part of the Lesser Khingan Mountains, the central-northern part of the Songnen Plain, and the Sanjiang Plain. The average county-level soybean yield for each cluster from 2011 to 2021 was calculated (Figure 9), and the Mann–Kendall trend test was performed (Table 2). The average time series of Cluster 1 showed a certain downward trend, but it did not pass the significance test. In contrast, the average time series of Cluster 2 demonstrated a significant upward

trend. The temporal changes in soybean yield in various counties of Heilongjiang Province have obvious regional characteristics. This also partially explains the overall increase in soybean yield in Heilongjiang Province, but the upward trend is not significant.



**Figure 8.** Time series clustering of county-level soybean yield in Heilongjiang Province from 2011 to 2021.



Figure 9. Average county-level soybean yield time series for each cluster.

Sample	Inclination $\beta$	$Z_c$	Significance
Cluster 1	-850.22	-0.15	Nonsignificant
Cluster 2	6486.7	2.49	Significant increase

Table 2. The Mann–Kendall trend test of average time series for each cluster.

In addition, the Mann-Kendall trend test was conducted on the soybean yield series of each county-level administrative unit in Heilongjiang Province (Figure 10). From 2011 to 2021, 33.33% of county-level administrative units in Heilongjiang Province experienced a decreasing trend in soybean yield, while 66.67% of county-level administrative units showed an increasing trend in soybean yield. Among them, there were 23 counties where soybean yields increased significantly. These counties are mainly located in the northern part of the Songnen Plain and the western part of the Sanjiang Plain, including most areas of Suihua, Hegang, and Shuangyashan cities, as well as the central-southern part of Heihe City, the southern part of Qiqihar City, and the eastern part of Daqing City. These areas have become the major contributors to the growth of soybean production in Heilongjiang Province. The counties with a significant decrease in soybean yield were scattered and the number was relatively small, including only Kedong, Tieli, Boli, and Dongning. At the time series clustering level, the counties with a significant decrease in soybean yield all belonged to Cluster 1, while the counties with a significant increase in soybean yield all belonged to Cluster 2. In Cluster 1, 57.14% of counties showed a downward trend in soybean yield, with only 10 exceptions. In Cluster 2, all counties showed an upward trend in soybean yield, with 57.5% of counties passing the significance test at the 0.1 level.



**Figure 10.** Variation tendency of soybean yield in counties of Heilongjiang Province from 2011 to 2021.

4.2. Influencing Factors of Soybean Production in Heilongjiang Province

## 4.2.1. Determination of Influencing Factors

The soybean production process combines natural reproduction and economic reproduction and is influenced by many factors [8]. This study macroscopically explored the influencing factors of soybean production in Heilongjiang Province at the provincial level. Based on the principles of indicator scientificity and data availability, soybean yield was used to characterize soybean production level, and 13 variables from eight dimensions were selected as influencing factors for analysis (Table 3). The time span of the data was from 2011 to 2021.

Table 3. Influencing factors and descriptions.

Dimension	Influencing Factors	Symbol	Description	Unit	Relationship
Climatic condition	Sunlight hours	X1	Obtained by averaging the sunlight hours of 13 major prefecture-level cities in Heilongjiang Province from May to September. The soybean growing season in Heilongjiang Province is from May to September.	h	+
	Average temperature	X2	Obtained by averaging the temperatures of 13 major prefecture-level cities in Heilongjiang Province from May to September.	°C	+
	Precipitation	Х3	Obtained by averaging the precipitation of 13 major prefecture-level cities in Heilongjiang Province from May to September.	mm	The closer to 600 mm, the better
Natural disaster	Crops-hitting disaster area	<i>X</i> 4	Area of crops influenced by natural disasters in Heilongjiang Province. Disaster types include drought, floods, hail, freezing and typhoons.	hm <sup>2</sup>	_
Planting income	Soybean cultivation income	X5	Obtained by subtracting cash costs from the total output value and adding soybean subsidies, representing the net income per hectare of soybean cultivation in Heilongjiang Province.	yuan/hm <sup>2</sup>	+
Market condition	Local soybean prices	X6	Average selling price of local soybeans in Heilongjiang Province each year	yuan/kg	+
Technology research	Number of soybean patents	Х7	The number of soybean-related patents filed in Heilongjiang Province each year	unit	+
Industrial development	Number of newly established soybean enterprises	X8	The number of newly established soybean-related enterprises in Heilongjiang Province each year	unit	+
International trade	Soybean import volume	X9	Soybean import volume in Heilongjiang Province each year	t	_
	Price ratio of imported soybeans to local soybeans	X10	Average price of imported soybeans in Heilongjiang Province/average price of local soybeans in Heilongjiang Province	%	+
Competitive crop	Maize yield	X11	Maize yield in Heilongjiang Province each year	t	_
	Price ratio of local soybeans to local maize	X12	Average price of local soybeans in Heilongjiang Province/average price of local maize in Heilongjiang Province	%	+
	Income difference between maize and soybeans	X13	cultivation in Heilongjiang Province–net income per hectare of soybeans cultivation in Heilongjiang Province	yuan/hm <sup>2</sup>	_

Note: + represents a positive correlation; - represents a negative correlation.

As an agricultural production behavior, soybean cultivation has typical natural attributes and is greatly influenced by factors such as climatic conditions and natural disasters. In terms of climatic conditions, soybeans are heliophilous and short-day crops. They are not shade-tolerant and are highly sensitive to the length of sunlight. Sunlight hours were used to characterize the sunshine conditions of soybean production in Heilongjiang Province. The sunlight hour data were from the Heilongjiang Statistical Yearbook. Soybeans are also warm-season crops, and high and low temperatures should be avoided throughout their entire growth period. When the temperature is lower than 13 °C or more than 40 °C, it will affect the yield and quality of soybean [56]. The average temperature was used to reflect the temperature conditions of soybean production in Heilongjiang Province. The average temperature data were from the Heilongjiang Statistical Yearbook. For Heilongjiang Province, improving the utilization rate of light and heat resources is an effective way to achieve high soybean yields. Therefore, there is generally a positive relationship between the two and soybean yield in Heilongjiang Province [57,58]. Soybeans are sensitive to moisture and require more water for growth than other crops. For soybean planting areas in Northeast China, the soybean yield is highest when rainfall is approximately 600 mm during the soybean growth period from May to September [59]. Precipitation was used to represent the moisture conditions of soybean production in Heilongjiang Province. The precipitation data were from the Heilongjiang Statistical Yearbook. In addition, natural disasters are an important reason for the reduction in soybean production. The crops-hitting disaster area was used to reflect the severity of natural disasters in Heilongjiang Province. The crops-hitting disaster area data were from the China Rural Statistical Yearbook.

Soybean cultivation is also considered an agricultural management activity with clear socioeconomic attributes. Soybean yields are determined not only by natural environmental conditions but also by farmers' land management decisions. Planting income, market conditions, international trade, competitive crops, technology research, and industrial development are all important aspects that affect farmers' willingness to plant soybeans in Heilongjiang Province.

Planting income, market conditions, technology research, and industrial development often have a positive impact on soybean production in Heilongjiang Province. As soybean farmers prioritize profitability, the higher their income is, the greater their motivation to participate in soybean cultivation. The rise in soybean market prices directly improves the profitability of soybean farmers and enhances their confidence in soybean cultivation. Technology research can improve the yield and quality of soybeans, increase the efficiency of planting operations, and ensure income growth for farmers. Industrial development is conducive to broadening sales channels and increasing the added value of products. Increased income, favorable market conditions, technological progress, and prosperous industries will all attract more farmers to enter the soybean cultivation sector, thereby increasing soybean yields. In terms of planting income, soybean cultivation income was used to characterize the profitability of soybean production in Heilongjiang Province. The total output value and cash cost per hectare of soybeans were from the Compilation of National Cost and Revenue of Agricultural Products, and the subsidy per hectare of soybeans was from the Finance Bureau of Heilongjiang Province. In terms of market conditions, local soybean prices were used to represent the overall market situation of soybeans in Heilongjiang Province. The local soybean price data were from the Compilation of National Cost and Revenue of Agricultural Products. In terms of technology research, the number of soybean patents was used to reflect the technological output status in the soybean field in Heilongjiang Province. The patent data were from the Patenthub website (https://www. patenthub.cn/ (accessed on 1 June 2023)). In terms of industrial development, the number of newly established soybean enterprises was used to characterize the development trend of the soybean industry in Heilongjiang Province. The enterprise data were from the Qichacha website (https://www.qcc.com/ (accessed on 1 June 2023)).

International trade and competitive crops often have a negative impact on soybean production in Heilongjiang Province. In terms of international trade, compared with that

of major soybean-producing countries such as the United States and Brazil, Heilongjiang's soybean production scale is limited. Soybean varieties grown in Heilongjiang Province are non-transgenic soybeans, which leads to higher production costs and lower soybean yields. Therefore, they lack a price advantage in market competition. The influx of lowpriced imported soybeans compresses the market space of domestic soybeans, suppresses local soybean market prices, and exerts a crowding-out effect on soybean production in Heilongjiang Province. The soybean import volume was used to represent the soybean import scale in Heilongjiang Province, while the price ratio of imported soybeans to local soybeans was used to reflect the price gap between the two. The soybean import data were from the Heilongjiang Statistical Yearbook. In terms of competitive crops, maize and soybeans, which are both dryland crops, have the most intense competition in Heilongjiang Province. In most years, the actual returns of planting maize are higher than those of soybeans, which affects farmers' planting decisions. Farmers replace a portion of soybean acreage with high-yielding maize, resulting in a reduction in soybean production. Maize yield was used to represent the scale of maize production in Heilongjiang Province. The maize yield data were from the Heilongjiang Statistical Yearbook. The price ratio of local soybeans to local maize was used to reflect the price gap between the two. The local maize price data were from the Compilation of National Cost and Revenue of Agricultural Products. The income difference between maize and soybeans was used to reflect the actual planting profit gap between the two, and this variable takes into account the impact of differentiated subsidies for maize and soybeans in Heilongjiang Province. The total output value and cash cost per hectare of maize were from the Compilation of National Cost and Revenue of Agricultural Products, and the subsidy per hectare of maize was from the Finance Bureau of Heilongjiang Province.

#### 4.2.2. Analysis of Influencing Factors

Grey relational analysis is essentially based on the similarity of geometric shapes of sequence curves to judge the closeness of the relationship. Therefore, it is crucial to forward-process the raw data based on the correlation relationship between each comparability sequence and the reference sequence. *X*4, *X*9, *X*11, and *X*13 are negative indicators. The higher the values of these indicators are, the greater the negative impact on soybean production in Heilongjiang Province. *X*1, *X*2, *X*5, *X*6, *X*7, *X*8, *X*10, and *X*12 are positive indicators. The higher the values of these indicators are, the greater the positive impact on soybean production in Heilongjiang Province. *X*3 is an intermediate indicator. The closer the value is to 600 mm, the more favorable it is for soybean production in Heilongjiang Province. Therefore, intermediate and negative indicators must be processed before grey relational analysis can be carried out.

Agricultural production has periodic and seasonal characteristics [60]. Different from climatic conditions and natural disasters, socioeconomic factors such as planting income, market conditions, international trade, competitive crops, technology research, and industrial development often indirectly affect soybean yields by affecting farmers' planting decisions. Farmers need to make planting decisions early in the year. The previous year's market trends and the current year's market expectations are often used as reference information. However, the actual data for this year are mostly released after farmers' planting activities are implemented, with a significant time lag. In addition, factors such as information asymmetry, lack of professional knowledge and skills, blind conformity, and uncertainty in the agricultural production process also make farmers' planting decisions more difficult. This year's soybean production is directly affected by this year's climatic conditions and natural disasters, as well as by this year's and last year's socioeconomic factors.

Based on this, this study performed a comparative analysis of normal sequences, misaligned sequences, and moving smooth sequences. In the case of normal sequences, the reference sequence and the comparability sequences are contemporaneous. In the case of misaligned sequences, the reference sequence and some comparability sequences are contemporaneous. However, the comparability sequence data from the dimensions of planting income, market conditions, international trade, competitive crops, technology research, and industrial development are replaced by data from the previous year. In the case of moving smooth sequences, the reference sequence and some comparability sequences are contemporaneous. Only the comparability sequences of the above social-economic dimensions are processed by moving smoothing, with a moving period of 2 years. The processed data are the average of the original data from the same period and the previous period. The average grey relational grade between soybean yield and influencing factors in Heilongjiang Province was calculated based on different sequences (Table 4). The study revealed that the average grey relational grade obtained based on moving smooth sequences was significantly higher than those of normal sequences and misaligned sequences, and the difference between the average grey relational grades of the latter two sequences was relatively small. As a result, moving smooth sequences are most in line with the actual situation. Farmers' planting decisions are influenced by both past market conditions and current market expectations, and socioeconomic factors have aftereffects on soybean planting decisions.

**Table 4.** Average grey relational degree between soybean yield and influencing factors in Heilongjiang Province.

Sequence Type	Average Grey Relational Grade
Normal sequence	0.739
Misaligned sequence	0.729
Moving smooth sequence	0.797

The grey relational grade between soybean yield and each influencing factor in Heilongjiang Province was calculated based on moving smooth sequences (Table 5). Influencing factors are divided into primary, secondary and general factors based on the numerical value of grey relational grade, and the classification method is the natural breakpoint method. Among them, X1, X12, X2, X7, X10, X5, X6, and X8 are primary influencing factors, X3 and X9 are secondary influencing factors, and X13, X4, and X11 are general influencing factors. Overall, sunlight hours (X1) had the strongest correlation with soybean yield in Heilongjiang Province, while maize yield (X11) had the weakest correlation. In terms of natural geographical factors, the impacts of sunlight hours (X1) and average temperature (X2) on soybean yield were significantly higher than those of precipitation (X3) and crops-hitting disaster areas (X4). In terms of socioeconomic factors, compared with scale indicators such as maize yield (X11) and soybean import volume (X9), the soybean yield in Heilongjiang Province was more sensitive to the price ratio of local soybeans to local maize (X12), as well as the price ratio of imported soybeans to local soybeans (X10). The impact of these two price ratios on soybean yield in Heilongjiang Province was even higher than those of soybean cultivation income (X5) and local soybean prices (X6). Among them, the price ratio of local soybeans to local maize (X12) had a higher impact than the price ratio of imported soybeans to local soybeans (X10). Technology research and industrial development also had a significant positive impact on soybean yield in Heilongjiang Province. The number of soybean patents (X7) and the number of newly established soybean enterprises (X8) were both primary influencing factors, but the influence of X7 was higher than that of X8. In contrast, the income difference between maize and soybeans (X13), crops-hitting disaster area (X4), and maize yield (X11) had a relatively small impact on soybean yield in Heilongjiang Province.

Influencing Factors	Grey Relational Grade	Rank
Sunlight hours X1	0.915	1
Price ratio of local soybeans to local maize X12	0.883	2
Average temperature X2	0.874	3
Number of soybean patents X7	0.863	4
Price ratio of imported soybeans to local soybeans X10	0.847	5
Soybean cultivation income X5	0.846	6
Local soybean prices X6	0.834	7
Number of newly established soybean enterprises X8	0.817	8
Precipitation X3	0.758	9
Soybean import volume X9	0.753	10
Income difference between maize and soybeans X13	0.693	11
Crops-hitting disaster area X4	0.665	12
Maize yield X11	0.610	13

**Table 5.** Grey relational degree between soybean yield and each influencing factor in Heilongjiang Province from 2011 to 2021.

## 5. Discussion

#### 5.1. Spatial Evolution Mechanism of Soybean Production in Heilongjiang Province

The spatial pattern of soybean production in Heilongjiang Province is dynamically changing and is mainly characterized by three features: the shift of the production center to the northwest, spatial agglomeration of core production areas, and spatial differentiation in yield changes.

- 1. With global warming and advances in agricultural technology, the soybean production center in Heilongjiang Province is constantly shifting to the northwest [61]. Soybeans have a strong adaptability to the environment, but their distribution is also restricted by natural conditions. Except for non-irrigated areas where the active accumulated temperature (≥10 °C) is below 1900 °C and the precipitation is below 250 mm, soybean cultivation can be found in almost all agricultural areas [25]. Heilongjiang Province has favorable conditions, such as simultaneous heat and precipitation, large temperature differences between day and night, and long sunshine hours in summer. In addition, soybeans exhibit a strong tolerance to cold temperatures. As long as suitable varieties are selected, soybeans can still achieve high yields even in the frigid climate of northern Heilongjiang Province [62]. If other crops, such as maize or rice, are grown in this cold region, their stability is inferior to that of soybeans [63].
- 2. The current soybean production hot spots are concentrated at the junction of Heihe City, Suihua City, and Qiqihar City [64]. With Hailun and Suiling as the southern boundaries and Aihui as the northern boundary, the type of cultivated land in this area is mainly dry land. It is not a dominant planting area for maize. In contrast, soybean production has a greater advantage. The area to the north of Aihui belongs to the Greater Khingan Mountains forest region, with limited arable land resources and an active accumulated temperature (≥10 °C) below 1900 °C. Its natural conditions cannot meet the needs of large-scale soybean cultivation. The latitude of northeastern Heilongjiang Province is relatively low, and the cultivated land type is mainly paddy fields. Rice is the main crop in this area [65]. In the southern part of Heilongjiang Province, where the accumulated temperature is higher, rice and maize cultivation have higher benefits, while soybeans lack a competitive advantage [25].
- 3. From 2011 to 2021, there was a significant spatial difference in soybean yield fluctuations in different counties of Heilongjiang Province. Overall, the growth trend of soybean yield in northern counties was higher than that in southern counties. The most significant increase is observed in the northern part of the Lesser Khingan Mountains, the central-northern part of the Songnen Plain, and the Sanjiang Plain [66]. These areas are rich in arable land resources and have a solid foundation for agricultural production. The majority of the low-yield, low-quality, and low-efficiency corn

and rice production areas in Heilongjiang Province are concentrated here. At the same time, these areas are also the core regions for promoting the rotation between soybeans and other crops in Heilongjiang Province. In other county-level administrative units, soybean yield changes are not significant due to factors such as planting income, topography, and cultivated land types. Only soybean yields in Kedong, Tieli, Boli and Dongning decreased significantly.

#### 5.2. Temporal Evolution Mechanism of Soybean Production in Heilongjiang Province

From 2011 to 2021, the soybean yield in Heilongjiang Province showed a non-significant fluctuating upward trend (Figure 11). Depending on the direction of yield changes, the research period can be divided into 7 specific time periods, as follows:

- 1. From 2011 to 2013, the soybean yield in Heilongjiang Province declined year by year, which was caused by factors such as rising soybean planting costs, low comparative returns, crop rotation, international market shocks, and high national grain reserve standards. The production factor cost of soybean cultivation is constantly increasing, and the comparative benefit is lower than those of competitive crops such as rice and maize [67]. Soybean cultivation requires crop rotation to reduce pests and diseases, prevent soil nutrient imbalance, and eliminate the toxic effects of root and microbial secretions. As a result, soybean acreage undergoes periodic reductions [68]. Imported soybeans have the characteristics of low prices and high oil extraction rates, which attract large-scale oilseed processing enterprises to concentrate in coastal areas. This has a crowding-out effect on soybean production in Heilongjiang Province [69]. Although the temporary soybean purchasing and storage policy to some extent guarantees the income of soybean farmers, the national purchasing and storage agencies have high quality requirements for soybeans. Farmers still need to bear the expenses of shortdistance transportation, grain losses, accommodation, etc. Therefore, the problem of limited soybean sales still exists [70]. In addition, the precipitation in Heilongjiang Province increased abnormally in the winter of 2012, resulting in snow covering a wide area and persisting for a long time. As a result, severe soil waterlogging occurred in the spring of 2013, and spring plowing activities were severely disrupted [71]. In the summer of 2013, Heilongjiang Province experienced frequent rainfall and insufficient sunlight. Some major soybean-producing areas suffered from floods, which greatly affected soybean production [72].
- 2. In 2014, soybean yield showed a recovery of growth. The weather conditions in 2014 were favorable for soybean planting in Heilongjiang Province. The soil moisture was good, the temperature was normal, and the sunshine was ample. The growth and development of soybeans was better than that in previous years [73]. In the same year, Heilongjiang Province changed its temporary soybean purchasing and storage policy to the soybean target price policy.
- 3. In 2015, due to the impact of various factors, such as the low comparative benefits of soybean cultivation and the import of foreign transgenic soybeans, an increasing number of farmers in Heilongjiang Province switched to planting maize. In addition, the soybean target price policy temporarily did not have a significant impact on the increase in soybean production in Heilongjiang Province, and soybean yield declined [74].
- 4. In 2016 and 2017, the soybean yield in Heilongjiang Province increased. In November 2015, the Ministry of Agriculture and Rural Affairs of China issued guiding opinions on the structural adjustment of maize in the 'Liandaowan' areas, which promoted the increase in the soybean planting area in Heilongjiang Province [75]. In March 2016, China officially canceled the temporary maize purchasing and storage policy in the three provinces of Northeast China and the Inner Mongolia Autonomous Region. The cancellation of the temporary purchasing and storage policy led to the expectation of falling maize prices, and some farmers switched to planting soybeans instead. In

addition, Heilongjiang Province launched a pilot subsidy for maize-soybean rotation in 2016, which further strengthened farmers' willingness to plant soybeans.

- 5. In 2018, the soybean yield in Heilongjiang Province decreased. Maize prices continued to rise at the end of 2017, which resulted in a decline in farmers' interest in planting soybeans. In addition, the northwestern region of Heilongjiang Province suffered from low temperatures and frosty weather in September 2018, which also led to a certain reduction in soybean yields [76].
- 6. In 2019 and 2020, the soybean yield in Heilongjiang Province increased rapidly. In 2019, China launched the second round of the soybean revitalization plan and issued an implementation plan, which clearly stated the goal of increasing the effective supply of soybeans. Since 2018, the difference in producer subsidies between soybeans and maize has widened in Heilongjiang Province. Soybean subsidies far exceed maize subsidies, resulting in a higher income of soybeans than of maize in 2018. Farmers' enthusiasm for planting soybeans increased, and soybean yield increased in 2019. On the basis of continuing to implement differentiated producer subsidies for maize and soybeans, the weather conditions for soybean cultivation in Heilongjiang Province in 2020 were ideal, resulting in a further increase in soybean yields.
- 7. In 2021, the soybean yield in Heilongjiang Province showed a downward trend. Rising maize prices in 2020 have led to a significant increase in maize profits. Farmers had a strong desire to expand maize planting, which squeezed out part of the soybean planting area [77].



Figure 11. Soybean yield in Heilongjiang Province from 2011 to 2021.

#### 5.3. Discussion on the Differences in Grey Relational Grade of Influencing Factors

Soybean production in Heilongjiang Province is influenced by multi-dimensional factors, and the action strength of different influencing factors is different.

## 5.3.1. Primary Influencing Factors

The primary influencing factors include sunlight hours (X1), the price ratio of local soybeans to local maize (X12), average temperature (X2), the number of soybean patents (X7), the price ratio of imported soybeans to local soybeans (X10), soybean cultivation income (X5), local soybean prices (X6), and the number of newly established soybean enterprises (X8).

- 1. Soybeans are crops that prefer light and warmth. Sufficient sunlight and suitable temperature are beneficial to the growth and maturity of soybeans. Due to the short frost-free period, the soybean varieties selected for planting in various regions of Heilongjiang Province are strictly restricted by temperature conditions. The farther north in Heilongjiang Province, the more farmers tend to choose soybean varieties with a shorter growing period and stronger cold-resistant characteristics [78]. The length of the growth period and the accumulated temperature basically determine the unit-yield level of soybeans [63]. Liu and Dai similarly found that temperature and sunlight are the main factors influencing soybean phenology [79].
- 2. The soybean yield in Heilongjiang Province is extremely sensitive to the price ratio of local soybeans to local maize, as well as the price ratio of imported soybeans to local soybeans. The relative prices of local soybeans and local maize directly determine farmers' planting choices, while price fluctuations in the international soybean market profoundly affect the supply-demand relation of soybeans in Heilongjiang Province. The impacts of these two price ratios on soybean yield in Heilongjiang Province are even higher than those of soybean cultivation income and local soybean prices. The impact intensity of local maize is greater than that of imported soybeans. This is because Heilongjiang Province is located in the inland area. Compared to coastal areas, the transportation time of imported soybeans is longer, and the transportation cost is higher. As a result, the price advantage of imported soybeans is greatly reduced. In addition, the main uses of domestic soybeans and imported soybeans are different, and the substitution relationship is limited. Domestic soybeans are non-transgenic soybeans with a high protein content and are mainly used for soybean food processing. Imported soybeans have advantages in terms of oil extraction rate and are mainly used for oil extraction and feed production [80]. Due to the preference for green food, some consumers in the soybean market prefer higher-priced non-transgenic soybeans, which also enhances the development resilience of local soybeans in Heilongjiang Province [81]. The competition between local maize and local soybeans is very intense. The climatic conditions in Heilongjiang Province are also suitable for maize cultivation, and the comparative profit of maize is generally higher than that of soybeans. Faced with the realistic pressure of rising land transfer prices, farmers pursue higher profits and continuously expand maize cultivation areas, resulting in a decline in soybean yields.
- 3. Imported soybean prices and local maize prices have a greater impact on soybean yield in Heilongjiang than soybean import volume and maize yield. Imported soybean prices and local maize prices directly affect farmers' planting income, which subsequently affects the soybean yield in Heilongjiang Province by changing farmers' planting decisions. However, the effect mechanism of soybean import volume and local maize yield on soybean yield in Heilongjiang Province is more complicated, the influence process is more tortuous, and the influence intensity is relatively limited.
- 4. The number of soybean patents and the number of newly established soybean enterprises are also primary factors influencing soybean yield in Heilongjiang Province. The greater the number of soybean patents, the greater the investment in soybean research and the faster the technological progress. Technological innovations in soybean breeding, planting, processing, and other aspects collectively play a significant role in enhancing soybean yields [82]. The increasing number of newly established soybean enterprises indicates a positive development trend in the soybean industry and a strong demand in the soybean market. This stimulates more farmers to engage in soybean cultivation, which subsequently leads to an increase in soybean production in Heilongjiang Province. In addition, the agglomeration of soybean enterprises is the foundation of the soybean industry cluster. The upgrading of the industrial model will lead to many benefits [83], such as external economy, scale economy, and knowledge exchange, promote the revitalization of the soybean industry, and better transform resource advantages into economic advantages.

#### 5.3.2. Secondary Influencing Factors

Precipitation (*X*3) and soybean import volume (*X*9) are secondary influencing factors. With the development of agricultural irrigation facilities and precipitation forecasting technology, the ability of soybean production to cope with floods or droughts has increased, leading to a decrease in the correlation between precipitation and soybean yield [84]. As China's largest soybean-producing region, Heilongjiang Province has a high soybean yield and a limited demand for imported soybeans. As a result, its soybean yield is less affected by soybean import volume.

#### 5.3.3. General Influencing Factors

The income difference between maize and soybeans (*X*13), crops-hitting disaster area (*X*4), and maize yield (*X*11) are general influencing factors. First, Heilongjiang Province introduced differentiated subsidies for maize and soybeans, which partially narrows the income gap between maize and soybeans and reduces the correlation between this income gap and soybean yield [85]. Second, the statistical object of the crops-hitting disaster area in this paper is all crops in Heilongjiang Province, not just soybean crops, which also reduces the impact of this factor on soybean yield. Finally, farmers are often more responsive to the prices of competitive crops rather than their yields when making planting decisions, so the grey relational grade between maize yield and soybean yield is also relatively low.

## 5.4. Development Suggestions for Soybean Industry in Heilongjiang Province

#### 5.4.1. Cluster Development

First, Heilongjiang Province should focus on core soybean production areas such as Heihe, Suihua, and Qiqihar, accelerate the cultivation, introduction and agglomeration of soybean enterprises, form a synergistic relationship in the industrial chain, and build a cross-administrative soybean industry cluster. Second, cluster development should be characterized by non-transgenic high-protein edible soybeans. Finally, efforts should be made to vigorously develop deep processing of soybeans, extend the industrial chain, increase added value, achieve high quality and good prices in the market, drive farmers to increase production and income, and continuously improve the market competitiveness of soybeans in Heilongjiang Province.

#### 5.4.2. Production Optimization

First, the planting structure should be optimized, the area of maize in non-dominant cultivation areas and the area of rice with low yield, low quality and low efficiency should be reduced, and the area of soybeans should be appropriately increased. Second, the agricultural production technology service system should be improved. The organic combination of farmers and modern agriculture can be achieved through land trusteeship, joint management and other means. Finally, the construction of agricultural infrastructure should be accelerated, moderate-scale management should be promoted, the mechanization level of soybean production should be improved, and the cost of soybean cultivation should be reduced.

#### 5.4.3. Policy Guidance

First, differentiated producer subsidies for maize and soybeans should be implemented, and the maize-soybean rotation system should be promoted. Second, efforts should be made to increase support for soybean-leading enterprises and provide specific support in taxation, finance, etc. Finally, adhering to the "going out" development strategy, Heilongjiang Province can strengthen investment and trade cooperation with the Russian Far East in soybean production. Abundant arable land resources abroad could be utilized to establish soybean production bases and expand soybean supply channels.

## 5.4.4. Technology Investment

First, a government-industry-university-research institute development alliance should be established to enhance technology exchange and knowledge sharing. Second, biotechnology should be actively developed, high-quality soybean varieties should be cultivated, and farming methods should be innovated. Finally, the protection of black soil should be strengthened to provide environmental support and ecological security for the development of the soybean industry in Heilongjiang Province. The construction of regional agricultural brands such as "Black Soil Premium Products" and "Cold Zone Black Glebe" should be promoted.

#### 6. Conclusions

With a focus on soybean yield, this study integrated multi-source data and used a variety of statistical analysis methods, such as barycenter analysis, the Mann–Kendall test, the space–time cube, and grey relational analysis, to research the spatiotemporal evolution and influencing factors of soybean production in Heilongjiang Province from 2011 to 2021. On this basis, this study revealed the spatiotemporal evolution mechanism of soybean production in Heilongjiang Province, explored the reasons for the differences in the effects of influencing factors, and proposed suggestions for the development of the soybean industry from the perspectives of cluster development, production optimization, policy guidance, and technology investment. The main research conclusions are as follows.

- 1. In terms of the overall spatiotemporal variation, the center of gravity of county-level soybean yield in Heilongjiang Province moved towards the northwest over a distance of 16.82 km from 2011 to 2021. The soybean yield in the province experienced a mutation in approximately 2018, from a downward trend to an upward trend.
- 2. In terms of the spatiotemporal hot spot distribution, the spatiotemporal hot spots of county-level soybean yield in Heilongjiang Province were concentrated along the line from Hailun to Aihui. Specifically, Hailun and Suiling were consecutive hot spots; Bei'an, Wudalianchi, Nenjiang, Aihui, Kedong, and Keshan were intensifying hot spots; Sunwu and Baiquan were sporadic hot spots and Yi'an was a new hot spot.
- In terms of the spatiotemporal agglomeration pattern, the spatiotemporal agglomeration patterns of county-level soybean yield in Heilongjiang Province included only high-high clusters, only low-low clusters, only high-low outliers and multiple types.
- 4. In terms of the time series analysis, the temporal changes in soybean yield in various counties of Heilongjiang Province had obvious regional characteristics. There was no significant change in county-level soybean yield in the following regions: the Greater Khingan Mountains, the southern part of the Lesser Khingan Mountains, the southern part of the Songnen Plain, the Songhua River valley, and the mountainous and hilly areas of southeastern Heilongjiang Province. Meanwhile, the county-level soybean yield in the northern part of the Lesser Khingan Mountains, the southern part of the Songhua River valley, and the county-level soybean yield in the northern part of the Lesser Khingan Mountains, the central-northern part of the Songnen Plain, and the Sanjiang Plain showed a significant upward trend.
- 5. In terms of the action mode of influencing factors, socioeconomic factors had aftereffects on soybean planting decisions. This year's soybean production is directly affected by this year's climatic conditions and natural disasters, as well as by this year's and last year's socioeconomic factors.
- 6. In terms of the impact intensity of influencing factors, sunlight hours, the price ratio of local soybeans to local maize, average temperature, the number of soybean patents, the price ratio of imported soybeans to local soybeans, soybean cultivation income, local soybean prices, and the number of newly established soybean enterprises were the primary influencing factors. Precipitation and soybean import volume were secondary factors. The income difference between maize and soybeans, crop-hitting disaster areas, and maize yield were general influencing factors. For physical geographical factors, the impacts of sunlight hours and average temperature on soybean yield were significantly higher than those of precipitation and crop-hitting disaster areas. For socioeconomic factors, compared with scale indicators such as maize yield

and soybean import volume, the soybean yield in Heilongjiang Province was more sensitive to the price ratio of local soybeans to local maize, as well as the price ratio of imported soybeans to local soybeans. The impact of these two price ratios on soybean yield in Heilongjiang Province was even higher than those of soybean cultivation income and local soybean prices. Compared to that of imported soybeans, the impact of local maize was stronger. Technology research and industrial development also had a significant positive impact on soybean yield in Heilongjiang Province. The government's differentiated subsidy policy played an important role in stabilizing soybean production.

Based on Heilongjiang Province, this paper integrated data from agricultural reclamation systems and local authorities, considered both space and time, and enriched the current research on the spatiotemporal evolution and influencing factors of soybean production. However, this paper still has some limitations that demand a more thorough exploration in the future. On the one hand, due to the limitations of the collected data, the research scale of influencing factor analysis was limited to the provincial level, and the selection of influencing factors was also limited. Factors such as crop varieties, land quality, cultivation methods, and differences among farmers were not considered. On the other hand, the treatment of natural geographical factors was simplified in the analysis of influencing factors. The impact of different natural conditions in different regions of Heilongjiang Province on soybean production has not been deeply analyzed. It should be strengthened in the future.

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