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A Study on Spatial-Temporal Differentiation and Influencing Factors of Agricultural Water Footprint in the Main Grain-Producing Areas in China

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Abstract: It is an urgent scientific issue to explore the spatial and temporal differentiation and impact indicators of the agricultural water footprint in major grain-producing areas. Therefore, this study tries to use the water footprint theory to implement top-down calculation of the agricultural water footprint in major grain-producing regions from 2000 to 2019 and investigate the various impacts on the agricultural water footprint under the influence of spatial-temporal effects using spatial autocorrelation and the spatial Dubin model. The results indicate that from 2000 to 2019, the overall agricultural water footprint of China showed a fluctuating downward trend in an inverted *N* shape and demonstrated high–high and low–low spatial aggregation characteristics. There are notable characteristics, including high spatial dependence, spatial barriers, and path locking of the agricultural water footprint in most provinces and regions of the main grain-producing areas. Policy factors, water-saving technologies, social development, economic development, and industrial structure adjustment are all significantly and negatively correlated with the increase in the agricultural water footprint, while agricultural production and natural factors have a significant positive relationship with the agricultural water footprint. The spatial spillover effect of water-saving technologies, industrial restructuring, agricultural production, and natural factors is powerful. Therefore, a rationally optimized industrial structure, strengthened regional linkage of water resources management and control, and the promotion of efficient water infrastructure technology are important ways to inhibit the agricultural water footprint.

Keywords: main grain-producing areas; agricultural water footprint; spatial Dubin model

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1. Introduction

Water and food security are two of the vital global challenges of the future [1]. As a large, populous, and agricultural country, China is confronted with more severe pressures on water and food security. Future population growth, intensified competition for industry-used water, and climate change will all challenge water use in agriculture [2]. The 13 major grain-producing provinces, which are mainly responsible for China's agricultural production, supplied up to 78.89% of the country's grain production in 2019 but used less than 40% of water resources [3]. Under the current Chinese grain supply and demand structure, the main grain-producing areas have significant advantages in grain production in terms of water and soil resources, and they are bearing increasing pressure on agricultural water usage while exporting massive internal water resources to the external areas. However, considering the current accelerating frequency of extreme weather caused by climate change and the long-term ambiguity caused by COVID-19 since early 2020, agricultural ecological environment problems in China such as the degradation of arable land quality, agricultural non-point source pollution, soil erosion, and groundwater over-extraction have become increasingly prominent [4]. Agricultural water resources flow in regional agricultural product trade in the form of embedded water in the production, consumption, and trade process [5]. The water footprint theory can effectively quantify the real demand for water resources in regional agriculture, and it transforms the emphasis on traditional water resources from water resource supply management to product demand management. It broadens the traditional water resource evaluation system and provides a decision basis for the rational and efficient utilization of water resources [6]. In view of the great threat posed by a series of realistic dilemmas of agricultural water use to China's food security, it is necessary to use the water footprint theory to explore the spatial-temporal differences of agricultural water footprint and its influencing factors in China's major grain-producing areas.

In relevant studies on agricultural water footprint assessment methods, foreign assessment methods are mainly based on virtual water theory and life cycle theory, and the spatial scale of assessment contains global, national, provincial, and municipal levels. Abdullah et al. [7] argue that spatial variations of the water footprint of agricultural products can be employed to mitigate regional and global problems concerning water scarcity. After confirming the virtual water content of agricultural products, for the first time, Chapagain and Hoekstra [8] systematically calculated the agricultural water footprint from 1997 to 2001 at the global level, and further explored virtual water flows through commodity trade between countries. Then, Boulay et al. [9] proposed an agricultural product water footprint calculation method based on the life cycle methodology and discussed the impact of land use form changes on blue water resources. Rodriguez et al. [10] found that the gray water footprint accounted for a higher proportion when they analyzed the potato water footprint in the pam-pean region of Argentina, so they suggested improving the efficiency of fertilizer application and regulating the regional agricultural production water footprint with more professional technical support and stricter groundwater control measures. Abdullah et al. [11] demonstrated the value of the water footprint accounting framework for such river basins with the case study of the Upper Euphrates River basin. Zhou et al. [12] believed that reforming rice cropping systems could mitigate the water footprint and enhance grain yield in central China. Tamea et al. [13] established a synthesis database for country-oriented water footprints based on 370 agricultural products to support the national and global agricultural water assessment. Deihimfard [14] quantified the water footprint of agroecological systems in 17 Iranian provinces located in arid or semi-arid regions. Hossain [15] calculated the water footprints of local fruits and vegetables in Victoria according to the Australian Water Footprint Assessment Manual framework.

In research on the influencing factors of the agricultural water footprint, many scholars tend to consider the influence of natural environmental factors and production technology factors on the agricultural water footprint. Bocchiola [16] explored the effects of natural factors such as precipitation amount, soil conditions, humidity, and wind speed on the water footprint of crops. Cao et al. [17] found that irrigation patterns and social factors are the main factors affecting the agricultural water footprint. In terms of production technology, Ababaei and Etedali [18] found that the total power of farm machinery and the application of agricultural materials such as pesticides and fertilizers have an outstanding influence on the blue water footprint of wheat, and technology has a notable positive influence on the green water footprint of wheat. The study of Rao et al. [19] indicated that improper irrigation, low fertilization, and improper farm water management resulted in a high water footprint of crops. Munro et al. [20] reduced the water footprint in crop production by applying soil mulching and drip irrigation and analyzed the influencing factors of spatial differentiation in crops, planting patterns, and soil and field management factors.

At present, studies on the assessment methods and influencing factors of the agricultural water footprint are of great value, but there are certain shortcomings, as follows: Most of the previous research was conducted at national or provincial levels, but research setting the main grain-producing areas as the research object is rare; few studies have concentrated on the spatial and temporal differentiation of the agricultural water footprint, especially on the spatial distribution and significant congregation of the agricultural water footprint;

study on the influencing factors of the agricultural water footprint failed to take the influence of spatial and temporal differences into consideration, and it is even rarer to adopt the spatial and temporal effects into the influencing factors analysis model. Therefore, based on the assessment of the agricultural water footprint in the main grain-producing areas, this paper utilizes the spatial autocorrelation method to explore the spatial and temporal differentiation characteristics, adopts the spatial and temporal effects in the influencing factor analysis model, and applies the spatial Durbin model to explore the driving impacts of each influencing factor on the agricultural water footprint.

The other parts of this paper are structured as follows: Section 2 contains the data methodology and data sources. Section 3 illustrates the empirical results and analysis. Section 4 demonstrates the conclusions and implications.

2. Research Methods and Data

2.1. Theoretical Framework

The measurement of the agricultural water footprint needs to consider the real consumption of water resources of regional agriculture and the cross-regional trade of virtual water, including the internal water footprint and the external water footprint. This paper explores the spatial-temporal differentiation characteristics of the agricultural water footprint by applying the SDM model and discusses the spatial effect as a critical influencing factor. The agricultural water footprint, as an indicator used to evaluate the effect of regional water resource utilization, is also affected by regional policies, water-saving technologies, production levels, social development, economic development, natural factors, etc. Among the above factors, the adjustment of policy factors, water-saving technologies, social development, economic development, and other factors could increase the efficiency with which water is used, thereby restraining the increase in the agricultural water footprint. This research analyzes the spatial-temporal differentiation of the agricultural water footprint in the main grain-producing areas in China based on the assessment of the agricultural water footprint, adopts the spatial factors in the influencing factor analysis model, and explores the influencing indicators of the agricultural water footprint in order to provide effective suggestions and solutions for breaking the spatial path dependence of the regional agricultural water footprint and exploring approaches for the regionally linked water resources management in the future. The theoretical framework of this paper is shown in Figure 1.

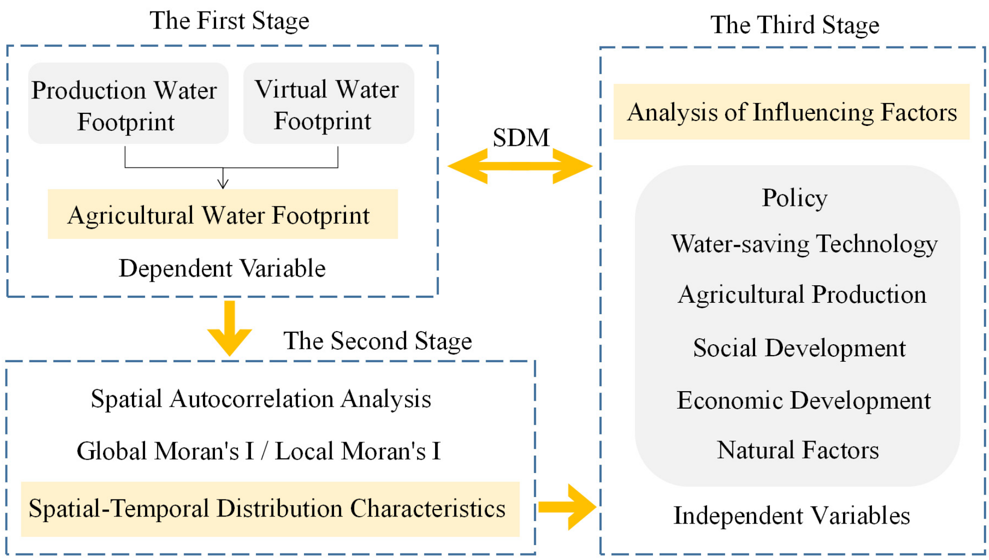

Figure 1. Theoretical framework of this paper.

2.2. Study Region

The main grain-producing area refers to the exclusive economic zone where natural conditions such as climate, geography, and soil, and economic conditions such as human resources, technology, and materials are more conducive to the cultivation of grain crops with high proportion, large production, and output of food crops. In 2003, China's Ministry of Finance designated 13 provinces as major grain-producing areas covering Northeast China, Huang-Huai-Hai, and the Yangtze river, which consist of Inner Mongolia, Jilin Province, Liaoning Province, Heilongjiang Province, Hebei Province, Jiangsu Province, Anhui Province, Shandong Province, Henan Province, Jiangxi Province, Hubei Province, Hunan Province, and Sichuan Province, the distribution of which is shown in Figure 2.

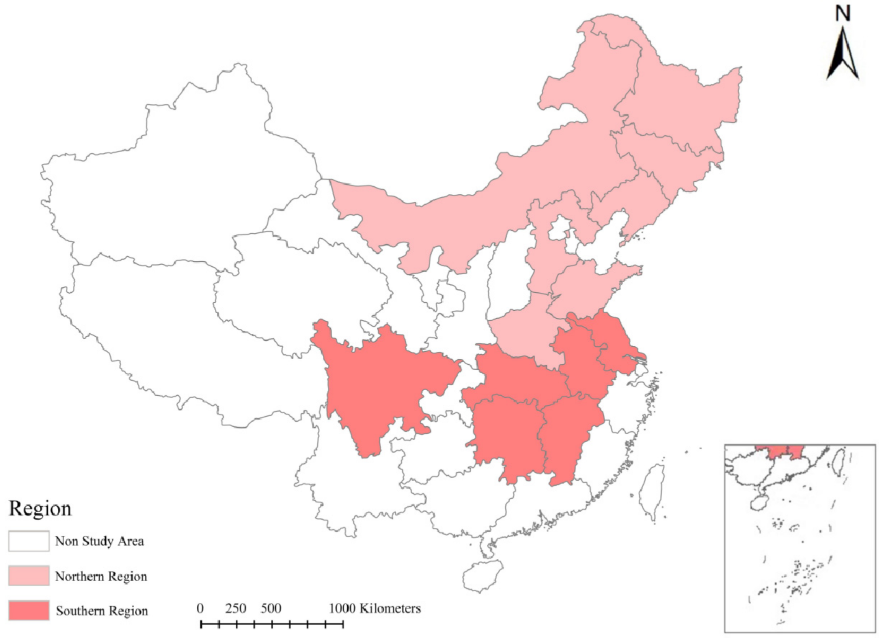

Figure 2. Study area considered to estimate the agricultural water footprint.

2.3. *Agricultural Water Footprint*

The agricultural water footprint is the total of the internal and external water footprint, in which the internal water footprint is the local agricultural production water minus the virtual water of local agricultural products, while the external water footprint is the entire virtual water of agricultural products from other places consumed by local residents [21]. The calculation formulas are listed as follows:

$$\begin{aligned} AWF_j^t &= IAWF_j^t + EAWF_j^t \\ &= AWFP_j^t - AWFO_j^t + AWFI_j^t \\ &= AWFP_j^t - AWFN_j^t \end{aligned} \tag{1}$$

In the above formula, t stands for the year, j stands for different regions, AWF_j^t stands for the agricultural water footprint (100 million m^3), $IAWF_j^t$ stands for the internal agricultural water footprint (100 million m^3), and $EAWF_j^t$ stands for the external agricultural water footprint (100 million m^3). $AWFP_j^t$ stands for the total amount of water required to produce agricultural products (100 million m^3), namely the total crop production water footprint. $AWFO_j^t$ stands for the virtual water output of agricultural products (100 million m^3), $AWFI_j^t$ stands for the agricultural virtual water input (100 million m^3), and $AWFN_j^t$ stands for the agricultural virtual water net output.

2.3.1. Agricultural Production Water Footprint

The agricultural production water footprint refers to the water consumption for producing a certain crop in a region within a specific time. The crop water footprint is the actual utilization sum of water resources during the growing process of a certain crop in a specific area, which can be distributed into the gray water footprint, blue water footprint and green water footprint [22]. The blue water and green water footprints are used for crop growth consumption of irrigation water and effective precipitation via the growth of crops, while the gray water footprint is the amount of freshwater consumed by diluting the pollutants produced in the agricultural production to meet the environmental water quality standards [23].

$$AWFP_{ij}^{t} = AWFP_{ij_{green}}^{t} + AWFP_{ij_{blue}}^{t} + AWFP_{ij_{grey}}^{t} \tag{2}$$

$$AWFP_{ij_{green}}^{t} = \frac{P_{je}^{t} \times S_{ij}^{t}}{\gamma_{ij}^{t}} \tag{3}$$

$$\begin{gathered} P_m \leq 250\text{mm}, P_{em} = P_m(125 - 0.2P_m)/125 \\ P_m > 250\text{mm}, P_{em} = 125 + 0.1P_m \end{gathered} \tag{4}$$

$$AWFP_{ij_{blue}}^{t} = IR_j^t \times S_{ij_G}^{t} = IR_j^t \times \frac{S_{jIR}^{t} S_{ij}^{t}}{S_{j_S}^{t}} \tag{5}$$

$$AWFP_{ij_{grey}}^{t} = \frac{\alpha \times AR_{ij}^{t}}{C_{\max} - C_{\text{nat}}} \tag{6}$$

In the above formula, S_{ij}^t stands for the sown area (1000 hectares) of crop i in period i and area j, γ_{ij}^t is the multi-cropping index, P_{je}^t stands for the effective precipitation amount in period t and area j, and P_m and P_{em} stand for the monthly precipitation amount and monthly effective precipitation amount (mm). IR_j^t stands for the water consumption for unit farmland irrigation in period t and area j (m^3/ha), S_{ijG}^t stands for the irrigated areas of crops (1000 hectares), S_{jIR}^t stands for effective irrigated areas (1000 hectares), S_{jS}^t stands for the total crops sown areas (1000 hectares), and S_{ij}^t stands for the sown area of crop i (1000 hectares). α stands for the nitrogen fertilizer leaching rate, namely the proportion of water pollution caused by nitrogen fertilizer, valued as 10%, AR_{ij}^t stands for the pure nitrogen element amount in nitrogen fertilizer consumption (kg) of crop i in each region, $C_{\max}$ is valued as 0.01 kg/m^3, and C_{nat} is valued as 0.

2.3.2. Agricultural Virtual Water Net Exports

The agricultural virtual water net exports represent the net output of virtual water generated when regional agricultural products are exported and imported at a certain time [24]. The calculation formula is listed as follows:

$$AWFN_{ij}^t = AWFO_{ij}^t - AWFI_{ij}^t = \sum WFP_{ij}^t (O_{ij}^t - I_{ij}^t) = \sum \frac{AWFP_{ij}^t}{Y_{ij}^t} (O_{ij}^t - I_{ij}^t) \tag{7}$$

In the above formula, $AWFN_{ij}^t$ stands for the net output of agricultural virtual water, $AWFO_{ij}^t$ is the agricultural virtual water output (100 million m^3), and $AWFI_{ij}^t$ is the agricultural virtual water input (100 million m^3). WFP_{ij}^t is the unit crop production water footprint (m^3/kg), Y_{ij}^t is the crop yield (kg), and O_{ij}^t and I_{ij}^t are the output and input (kg) of regional agricultural products, respectively.

2.4. Spatial Analysis Methods

2.4.1. Spatial Autocorrelation Method

The spatial autocorrelation method involves both global and local aspects, which are measured by the global Moran's I index and local Moran's I index separately [25]. The global Moran's I index generally reflects the spatial correlation characteristics of the whole region, and the local Moran's I index is used for evaluating the spatial aggregation characteristics in local areas.

The global spatial autocorrelation analysis can measure whether there is a spatial correlation at the overall level of the spatial unit. The calculation formula is computed as:

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \tag{8}$$

In the above formula,I is the global Moran's I index, W_{ij} is the spatial weight matrix, X_i and X_j are attribute values of each spatial unit, $\overline{x}$ is the mean value, S^2 is the sample variance, and n stands for the number of spatial units.

The local spatial autocorrelation method analyzes the aggregation characteristics of local space and specific attribute space. The calculation formulas are as follows:

$$I = \frac{x_i - \overline{x}}{S^2} \sum_{j \neq i}^{n} w_{ij}(x_j - \overline{x}) \tag{9}$$

$$S^2 = \frac{1}{n} \sum (x_i - \overline{x})^2 \tag{10}$$

When the local Moran's I index is greater than 0, it is believed that the high (low) valued regions and the high (low) valued adjacent regions are clustered. When the local Moran's I index is less than 0, it is considered that the high (low) valued regions and the low (high) valued adjacent regions are clustered.

2.4.2. Spatial Dubin Model

The spatial econometric model considering both temporal and spatial effects can effectively analyze the spatial influence of each factor on the explained variable [26]. This paper selects the spatial Dubin model (SDM) with fixed space and time to conduct spatial econometric analysis on the factors of the agricultural water footprint in the main grain-producing regions. The model is constructed as follows:

$$\ln Y_{it} = \rho \sum_{j=1}^{n} W_{ij} \ln Y_{jt} + \beta \ln X_{it} + \varphi \sum_{j=1}^{n} W_{ij} \ln X_{jt} + \mu_i + v_t + \varepsilon_{it} \tag{11}$$

In the above formula, Y_{it} stands for the explained variable, namely the agricultural water footprint value, X_{it} stands for the explanatory variable, namely the influencing factors that affect the agricultural water footprint, W_{it} stands for the spatial weight matrix, and μ_i and v_t stand for spatially fixed effects and the time-fixed effects.

2.5. Variable Selection and Data Sources

Referring to existing research, this study incorporates seven variables, including policy factors, agricultural water-saving technologies, agricultural production, economic and social development, and natural factors, into the influencing factor system, which is shown in Table 1. Data in this paper mainly come from the 2000–2019 related statistical yearbook, and statistical yearbooks of various provinces and regions. The precipitation data come from the related platform. The irrigation water data come from the related bulletins of various provinces and regions. The nitrogen fertilizer application amount for various crops per unit area comes from the *National Agricultural Product Cost and Benefits Data Compilation*. This paper adopts the linear prediction method to make up for the missing data during the sample period. The price-related indicators are deflated according to indicators in the year 2000. Similarly, missing data are also filled in using the linear prediction method.

Table 1. Selection and statement of influencing factor indicators.

Type	Index	Statement	Symbol	Unit	Data Source
dependent variable	agricultural water footprint		Y	100 million m^3	calculated in former part of this paper
Independe-nt variable	policy factors	proportion of irrigation and water conservancy expenditure in the total amount of water conservancy investment	X_1	100 million CNY	related Yearbook
	water-saving technologies	proportion of water-saving irrigation areas in the whole arable land	X_2	1000 hectares	related Yearbook
	agricultural production	total power of agricultural machinery	X_3	10,000 KW	related Yearbook
	social development	urbanization rate	X_4	%	related Yearbook
	natural factors	annual precipitation amount	X_5	mm	related Platform
	economic development	per Capita GDP	X_6	CNY/person	China Statistical Yearbook
	industry structure	proportion of agricultural output value in total regional output value	X_7	%	China Statistical Yearbook

3. Empirical Results and Analysis

3.1. Spatial-Temporal Differentiation Analysis of Agricultural Water Footprint in the Main Grain-Producing Areas

3.1.1. Calculation of Unit Production Water Footprint of Main Grain Crops in Main Grain-Producing Areas

The unit water footprint and its itemized water footprint values of major grain crops in the major grain-producing areas in the past 20 years were calculated, as shown in Table 2. By comparing the average unit water footprint of each crop, the water consumption types of each crop can be accurately classified. According to the unit agricultural production water footprint, the water consumption types of each crop are further divided into the following three categories: When $WFP > 2$, the unit crop production water footprint of crops is categorized as high water consumption; when $1 < WFP < 2$, the unit crop production water footprint of crops is categorized as medium water consumption; when $WFP < 1$, the unit crop production water footprint of crops is categorized as low water consumption [27]. According to the average value of the per unit crop production water footprint, rice and corn are medium-water-consumption crops, while beans and wheat are high-water-consumption crops. It can be found that in the composition of the water footprint per unit production, the per unit green water footprint of all food crops was higher than the blue water footprint, indicating that precipitation restricted food production.

Table 2. Water footprint per unit production of main grain crops in main grain-producing areas (m^3/kg).

Crops	Green Water Footprint	Blue Water Footprint	Grey Water Footprint	Total Water Footprint
Grain Crops	0.92	0.41	0.26	1.59
Rices	0.69	0.31	0.23	1.23
Wheats	1.53	0.67	0.24	2.44
Corns	0.93	0.41	0.24	1.58
Beans	2.61	1.14	0.09	3.84

It can be seen from Figure 3 that both the grain yield and production value in major grain-producing areas increased year by year from 2000 to 2019, which was mainly due to the increase in the yield of rice and corn, especially the high economic value of corn, which led to an increase in the agricultural production value in the main grain-producing areas.

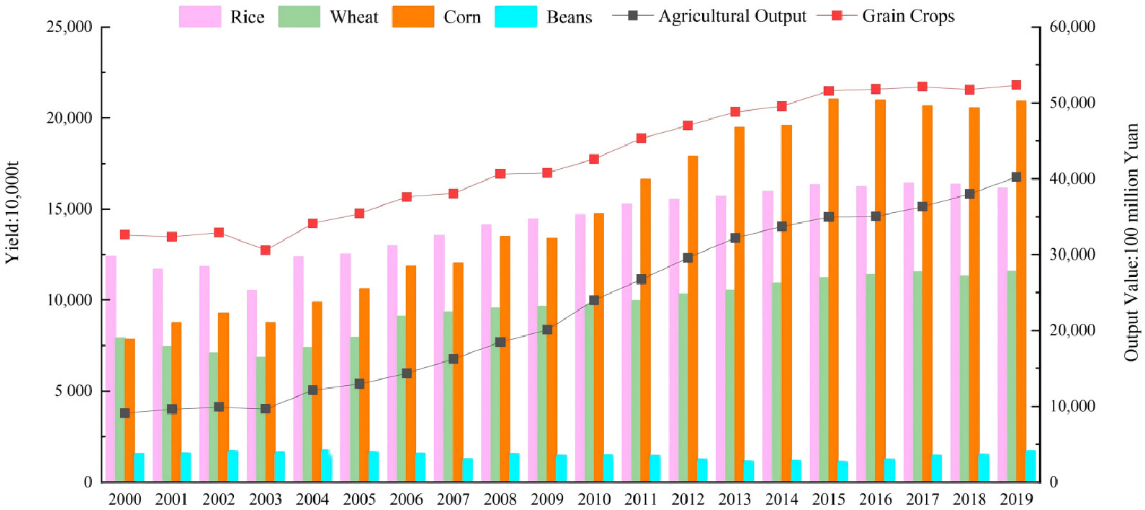

Figure 3. Grain yield and agricultural production value in major grain-producing areas from 2000 to 2019.

3.1.2. Time Series Variation Characteristics of the Agricultural Water Footprint in the Main Grain-Producing Areas

When calculating the agricultural water footprint in 13 major grain-producing regions from 2000 to 2019, this paper compares the production and consumption data of grain crops in each main grain-producing region. It is assumed that when the consumption of grain crops is less than the output of grain crops, the excess is exported to outside areas. Based on this, the agricultural water footprint values calculated in this research are shown in Figures 4 and 5.

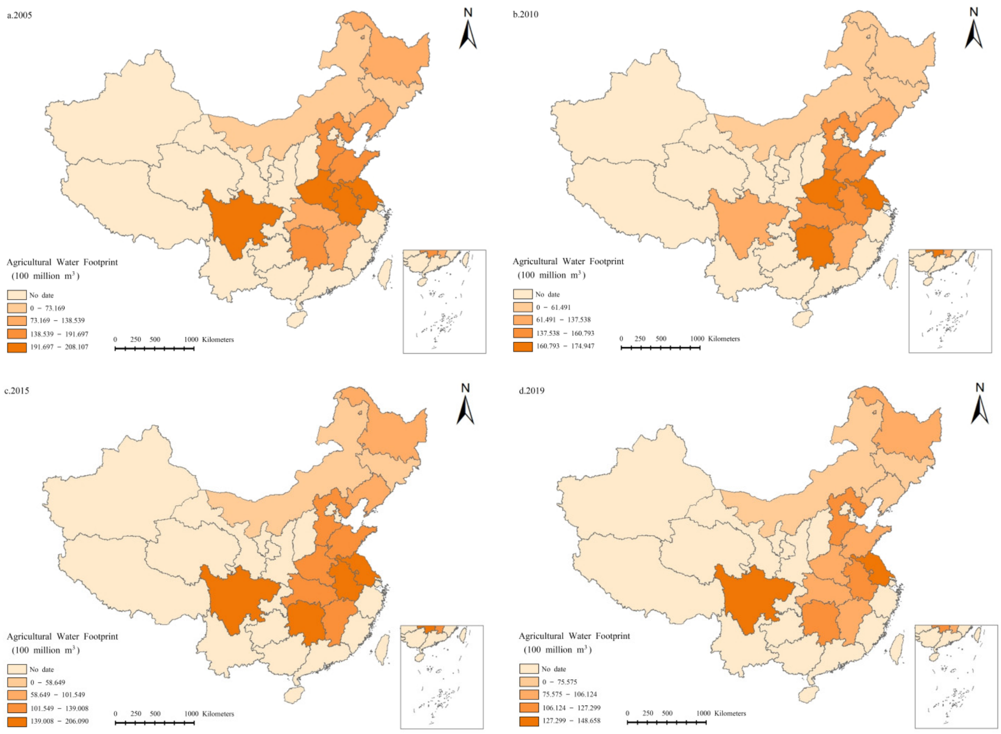

Figure 4. Agricultural water footprint of the main grain-producing provinces in typical year (100 million m^3).

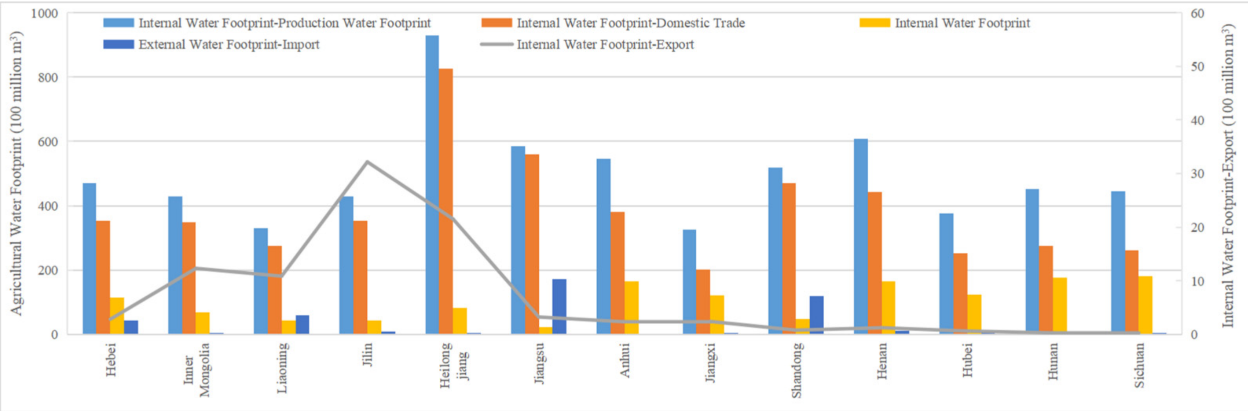

Figure 5. Agricultural water footprint in the main grain-producing provinces in the typical year.

Figure 6 reflects the time-series variation of the agricultural water footprint in the main grain-producing regions from 2000 to 2019. Taking the main grain-producing regions as a whole, the agricultural water footprint showed a fluctuating downward trend in an inverted *N* shape. From 2000 to 2005, the overall agricultural water footprints in the main grain-producing regions were comparatively high, and the regional differences were obvious. Agriculture water consumption was high. From 2006 to 2010, the high-water-consumption areas gradually moved closer to the low-water-consumption areas, and the agricultural water footprint differences between regions were reduced. The agricultural water footprint rebounded slightly from 2011 to 2016, and it gradually stabilized below 15 billion cubic meters after 2016. Compared with the beginning of the period, agricultural water consumption decreased to varying degrees.

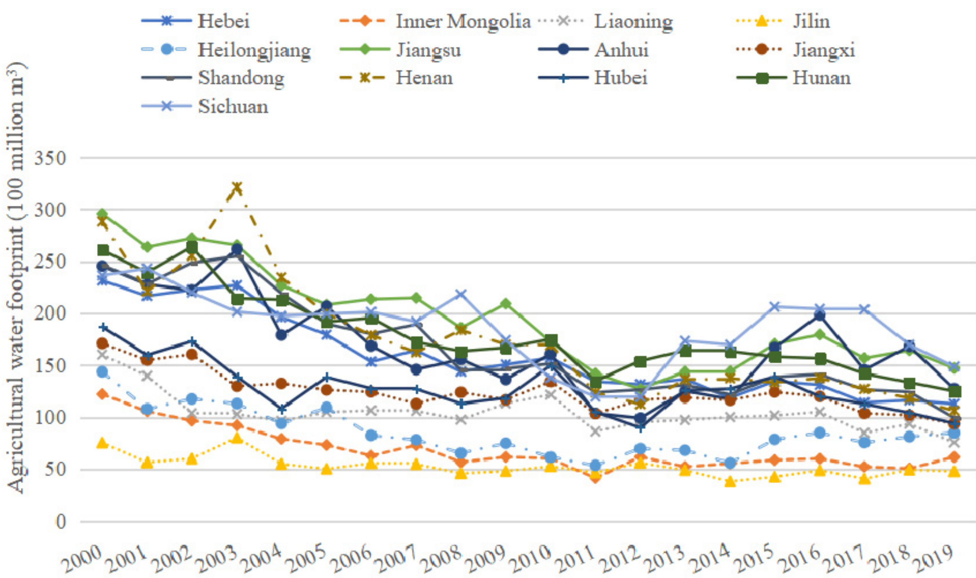

Figure 6. Time-series variation of the agricultural water footprint in the main grain-producing regions from 2000 to 2019.

3.1.3. Spatial Distribution Differences of Agricultural Water Footprint in the Main Grain-Producing Regions

Based on the measurement results of the global spatial autocorrelation Moran's I index, Table 3 shows the global Moran's I index significance level of the agricultural water footprint in the main grain-producing regions from 2000 to 2019 is between 0.000 and 0.016 and all below 1%, excluding the year 2019. It means that there is a significant positive spatial autocorrelation for the agricultural water footprint in the main grain-producing regions in most years, and there is an obvious spatial agglomeration effect from the overall perspective. From 2000 to 2019, the global Moran's I index of the main grain-producing areas showed a slow wavelike decrease, indicating that the spatial autocorrelation of the agricultural water footprint in the main grain-producing areas has weakened since 2000, but the overall spatial aggregation effect has become stronger.

Table 3. Global Moran's I index of agricultural water footprint in the main grain-producing areas.

Year	I	E (I)	sd (I)	z	*p*-Value
2000	0.563	−0.083	0.197	3.288	0.001
2001	0.576	−0.083	0.198	3.333	0.001
2002	0.622	−0.083	0.200	3.520	0.000
2003	0.576	−0.083	0.201	3.276	0.001
2004	0.517	−0.083	0.203	2.958	0.003
2005	0.599	−0.083	0.199	3.431	0.001
2006	0.582	−0.083	0.200	3.328	0.001
2007	0.569	−0.083	0.199	3.273	0.001
2008	0.520	−0.083	0.198	3.050	0.002
2009	0.480	−0.083	0.196	2.880	0.004
2010	0.742	−0.083	0.195	4.229	0.000
2011	0.609	−0.083	0.197	3.514	0.000
2012	0.423	−0.083	0.196	2.576	0.010
2013	0.578	−0.083	0.196	3.382	0.001
2014	0.589	−0.083	0.195	3.451	0.001
2015	0.575	−0.083	0.194	3.403	0.001
2016	0.518	−0.083	0.196	3.067	0.002
2017	0.489	−0.083	0.191	2.998	0.003
2018	0.513	−0.083	0.196	3.036	0.002
2019	0.386	−0.083	0.196	2.399	0.016

Regarding local spatial autocorrelation, the four quadrants of the local Moran's I scatter diagram stand for the four modes of spatial aggregation, namely high–high aggregation, low–high aggregation, low–low aggregation, and high–low aggregation (Figure 7).

On the whole, many regions are scattered in the first and third quadrants, displaying a strong spatial agglomeration effect as a whole. With the change in time, the spatial aggregation characteristics of the main grain-producing areas showed high–high aggregation and low–low aggregation, and the trend of polarization was obvious. Provinces and regions with a low agricultural water footprint, on the one hand, were similar in agricultural production and consumption. On the other hand, they transformed into low-value aggregation areas through regional cooperation, water-saving technologies, and resource management policies, and generated strong radiation and driving effects on neighboring areas. The main grain-producing provinces and regions with a high agricultural water footprint were usually high–high aggregation areas because of their high population density, high pressure on agricultural production and water resources development, and the impact of the high agricultural water footprint in adjacent areas.

In terms of various periods, during the 10th Five-Year Plan period, high–high agglomeration areas include Shandong, Jiangsu, Henan, Anhui, and Sichuan, while low–low agglomeration areas include Inner Mongolia, Jilin, Liaoning, and Heilongjiang, low–high agglomeration areas include Jiangxi and Hubei, and high–low agglomeration areas include Hebei and Hunan. During the 11th Five-Year Plan period, the spatial aggregation characteristics of the agricultural water footprint in the main grain-producing areas were strengthened, revealing distinct polarization. Except for Inner Mongolia and Northeast China, which are low–low aggregation areas, all the other provinces are high–high aggregation areas. During the 12th Five-Year Plan period, Jiangxi and Hubei moved to the second and fourth quadrants, respectively. During the 13th Five-Year Plan period, Hubei and Hunan moved to the second and fourth quadrants, respectively, compared with the previous period. The Northeast region and Huang-Huai-Hai region demonstrate more agglomeration effects, while the Yangtze river basin shows more discrete effects. Judging from the distribution of the main grain-producing provinces in various agglomeration areas, most provinces are quite stable, which means that there are notable characteristics including high spatial dependence, spatial barriers, and path locking of the agricultural water footprint in most provinces and regions of the main grain-producing areas.

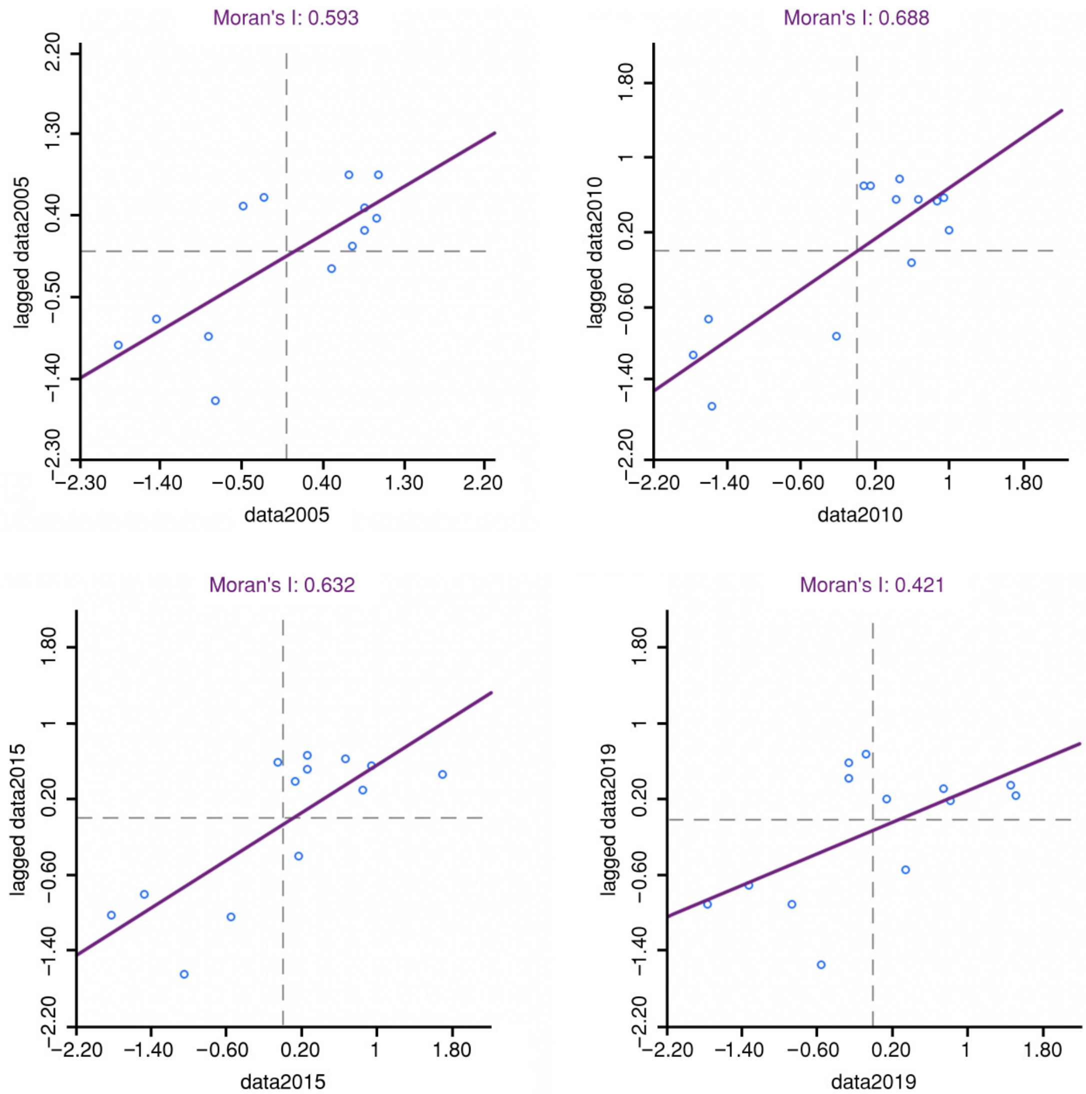

Figure 7. Moran I scatter diagram of agricultural water footprint in the main grain-producing areas from 2005 to 2019.

3.2. Analysis of Influencing Factors of Agricultural Water Footprint in the Main Grain-Producing Areas

3.2.1. Model Test

To ensure the accuracy of the influencing factors model for the agricultural water footprint in the main grain-producing regions and increase the credibility of the estimated results, this study carried out the spatial LM test, Hausman random effect, fixed-effect test, Wald test, and likelihood ratio LR test. Results show that the Spatial Dubin Model with fixed space and time should be adopted. The test results are listed in Table 4.

Table 4. Spatial econometric model test.

Test Type	Test Content	Statistical Value	p-Value	Conclusion
LM Test	LM (SEM) test	7.319	0.007	choose the SDM model
	Robust LM (SEM) test	12.343	0.000	
	LM (SAR) test	21.326	0.000	
	Robust LM (SAR) test	26.349	0.000	
Hausman Test	Hausman test	36.790	0.000	choose the SDM model and reject random effect
Fixed Effect Test	LR (ind or both) test	58.660	0.000	choose the SDM model, reject region fixed effect and time fixed effect, it is better with both fixed time and space
	LR (time or both) test	220.080	0.000	
Wald Test	Wald test SAR	26.080	0.000	choose the SDM model
	Wald test SEM	28.330	0.000	
LR Test	LR test SAR	24.900	0.000	SDM model cannot be degraded to SAR model
	LR test SEM	26.760	0.000	SDM model cannot be degraded to SEM model

3.2.2. Estimation Results and Analysis

Spatial Dubin model estimation results of the whole main grain-producing areas show that policy factors, water-saving technologies, social development, economic development, and industrial structure are significantly negatively correlated with the agricultural water footprint, while agricultural production and natural factors are markedly positively correlated with agricultural water footprint.

The policy factor that regards the proportion of irrigation and water conservancy expenditure in the total water conservancy investment as a proxy variable passes the 5% significance level test, and the coefficient is significantly negative. It means that the construction of agricultural irrigation and water resource facilities led by the central and local governments can restrain the agricultural water footprint increases.

The coefficient of water-saving technologies is −0.043, and it passes the 10% significance level test, confirming that water-saving irrigation technology can effectively restrain the agricultural water footprint of the main grain-producing regions and play a positive role in water sustainable utilization.

The coefficient of agricultural production, although under 1%, is markedly positive, meaning that the development of the agricultural production level with the total power of agricultural machinery as a proxy variable will lead to increases in the agricultural water footprint. The modernization of agricultural machinery and their increasing utilization rate will improve crop yields, thereby consuming more water resources.

The coefficient of social development is 0.215, and it passes the 1% significance level test. It means that with the acceleration of the urbanization process and the growth of the city's population, on one hand, agricultural water will be cut down. On the other hand, the change in the consumption structure of residents in the city and rural areas results in the need for higher-quality agricultural products as well as changes in the agricultural water footprint accordingly.

The coefficient of natural factors with the amount of precipitation as a proxy variable is distinctly positive, and it passes the 1% significance level test. According to the regression results, the annual precipitation amount has a significantly positive effect on the change in the agricultural water footprint. It means that areas with more abundant precipitation consume more green water in agricultural production and have a higher agricultural water footprint.

The coefficient of economic development is −0.424, and it passes the 1% significance level test. It shows that because of the economic growth, the financial, technical, and resource support brought by regional economic development to agricultural production, especially the application of water-saving technologies and the improvement of irrigation facilities, could all effectively restrain the increase in the agricultural water footprint.

The coefficient of industrial structure is −0.211 and it passes the 1% significance level test. Industrial restructuring is the main factor that restrains an increase in the agricultural water footprint. The increase in agricultural value-added production, the competitiveness enhancement of the agricultural industry in both domestic and foreign markets, and the sustainable development of agriculture are the main manifestations of agricultural industrial restructuring. The high-quality development of the agricultural economy in the main grain-producing regions will help to restrain the increase in the agricultural water footprint.

In order to further explore the regional differences of various influencing factors on the agricultural water footprint in the main grain-producing regions, this study divides the main grain-producing areas into the northern region and the southern region (Table 5). According to the spatial Dubin model estimation results at the subregional level, the coefficients of policy factors in the northern and southern regions are both significantly negative, which are −0.038 and −0.030, respectively. It means that agricultural irrigation and water conservancy expenditures pose deeper influences on restraining the agricultural water footprint in the northern region than in the southern region. The coefficients of water-saving technologies in the northern and southern regions both pass the 5% significance level test, and the absolute coefficient value of the southern part of the region is significantly larger than that in the northern region. It means that the driving effect of water-saving technologies in the northern region is significantly lower than that in the southern region. The coefficients of social development and natural factors in both northern and southern regions are consistent overall, and both of them pass the significance test. Different from the whole situation, the coefficients of agricultural production and industrial restructuring in the northern region and the coefficient of economic development in the southern region failed to pass the significance level test.

Table 5. Regression results of spatial Durbin model on the impact factors of agricultural water footprint in major grain-producing regions.

Variable	Main Grain-Producing Areas		Northern Region		Southern Region	
	Coefficient	p-Value	Coefficient	p-Value	Coefficient	p-Value
$\ln X_1$	−0.027	0.031	−0.038	0.020	−0.030	0.054
$\ln X_2$	−0.043	0.053	−0.076	0.012	−0.101	0.031
$\ln X_3$	0.173	0.000	−0.079	0.383	0.222	0.000
$\ln X_4$	−0.215	0.000	−0.349	0.000	−0.215	0.000
$\ln X_5$	0.260	0.001	0.312	0.001	0.307	0.000
$\ln X_6$	−0.424	0.000	−0.654	0.001	0.169	0.692
$\ln X_7$	−0.211	0.000	−0.127	0.226	−0.586	0.000
$W \times \ln X_1$	−0.001	0.969	0.040	0.287	−0.022	0.451
$W \times \ln X_2$	−0.086	0.063	−0.179	0.003	−0.114	0.185
$W \times \ln X_3$	0.210	0.036	0.217	0.405	0.515	0.000
$W \times \ln X_4$	−0.092	0.079	−0.330	0.046	−0.059	0.104
$W \times \ln X_5$	0.296	0.017	0.198	0.263	−0.146	0.312
$W \times \ln X_6$	−0.200	0.361	−1.050	0.007	−0.507	0.001
$W \times \ln X_7$	−0.289	0.010	−0.338	0.080	0.008	0.972

3.2.3. Decomposition Effect Analysis

Judging from the decomposition results for the whole main grain-producing area, the spatial spillover effects of water-saving technologies, agricultural production, natural factors, and industrial structure are strong. The details are listed as follows.

The direct effect coefficient of policy factors is negative, and it passes the 5% significance level test, but the indirect effect coefficient fails the test. This means that the increase in agricultural irrigation and water conservancy expenditure mainly restrains the increase in the local agricultural water footprint. The self-interested nature of local fiscal policies to support agriculture determines that all kinds of agriculture-supporting policies could only affect local agricultural production, and their spatial spillover effects are not strong.

Although the capital expenditure for the construction of irrigation facilities can effectively reduce the local agricultural water footprint to some extent, there is a large tendency to form path dependence and locking features in the region in the long run.

The direct and indirect effect coefficients of water-saving technologies are negative, and they pass the 10% and 5% significance level tests. It means that the development of water-saving technologies is not only beneficial to suppress the increase in the local agricultural water footprint, but also to inhibit the increase in the agricultural water footprint in adjacent areas through the negative spillover. Due to the positive externality of the technology, the local advanced irrigation and water-saving technologies spread to the outside and the advanced water resources management knowledge is diffused outward. Therefore, advanced water-saving technologies and knowledge will help to control the global agricultural water footprint.

The direct and indirect effect coefficients of agricultural production are both positive, and they pass the 1% and 5% significance level tests, respectively. This means that the extensive application of agricultural machinery will not only increase the local agricultural water footprint but also increase the agricultural water footprint in neighboring sites through positive spillover. The development of agricultural machinery technology in global regions has promoted the widespread application of agricultural machinery and equipment. In particular, the cross-regional services of agricultural machinery and equipment promote the mutual development of agricultural machinery in local areas, thereby increasing crop yields in local areas.

The direct effect coefficient of social development is -0.211 and it passes the 1% significance level test, while the indirect effect coefficient is not significant. It means that urbanization has the greatest influence on local agricultural water usage. Due to the similarity of household consumption between the adjacent regions in major grain-producing regions, changes in the consumption patterns and structures of residents have the most significant impacts on local agricultural water footprint.

The direct and indirect effect coefficients of natural factors are significantly positive under the 1% and 5% levels, respectively. It means that due to the similar natural climatic characteristics between the adjacent areas in the main grain-producing areas, the amount of precipitation has consistently positive effects on the agricultural water footprint of local and adjacent areas. The increase in local precipitation produces abundant surface water and groundwater resources, which cause positive spillovers through the water circulation system, and relieve the agricultural water pressure in adjacent regions.

The direct effect coefficient of economic development is significantly negative, but the indirect effect coefficient fails the significance level test. It means that economic development can significantly inhibit the local agricultural water footprint, but its spatial spillover effect is not strong enough to generate a negative effect on the agricultural water footprint in adjacent areas. The regional linkage of economic development does not work effectively, which works against the decrease in the agricultural water footprint in the main grain-producing regions.

The direct and indirect effect coefficients of the structure of the industry are both negative, and they pass the 1% and 5% significance level tests, respectively. It means that industrial restructuring can significantly inhibit the agricultural water footprint of local and adjacent areas.

Based on the regional decomposition results of the main grain-producing regions (Table 6), the direct and indirect effect coefficients of water-saving technologies and economic development in the northern region are both positive, and they all pass the 5% significance level test. It means that the growth of water-saving irrigation areas and economic development in the northern region are beneficial to restraining the increase in the local agricultural water footprint, and in the meantime, suppress the increase in the agricultural water footprint in adjacent areas through the negative spatial spillover effect. The direct effect coefficients of policy factors, social development, and natural factors all pass the 5% significance level test, which are -0.040, -0.329, and 0.303, respectively, while the indirect effect coefficients failed the test. It means that the increase in irrigation water conservancy expenditures and the improvement of the urbanization level in the northern region have outstanding effects on restraining the increase in the local agricultural water footprint. The direct and indirect effect coefficients of agricultural production in the southern region are both positive, and both of them pass the 1% significance level test. It means that the improvement of local agricultural mechanization in the southern region not only elevates the local agricultural water consumption but also promotes the increase in the agricultural water footprint in the adjacent areas through the positive spillover effect. The direct effect coefficients of policy factors, water-saving technologies, social development, natural factors, and industrial structure pass the 10% significance level test, and their indirect effect coefficients failed the test. It means that the spillover effect of these influencing indicators in the southern region is not strong enough.

Table 6. Decomposition effect results of influencing factors.

Region	Variable	Direct Effect		Indirect Effect		Total Effect	
		Coefficient	*p*-Value	Coefficient	*p*-Value	Coefficient	*p*-Value
Main Grain-producing Regions	$\ln X_1$	−0.027	0.038	0.001	0.971	−0.026	0.400
	$\ln X_2$	−0.042	0.075	−0.082	0.048	−0.123	0.014
	$\ln X_3$	0.168	0.000	0.198	0.029	0.366	0.000
	$\ln X_4$	−0.211	0.000	−0.073	0.113	−0.284	0.000
	$\ln X_5$	0.255	0.001	0.268	0.024	0.523	0.000
	$\ln X_6$	−0.419	0.000	−0.155	0.483	−0.574	0.033
	$\ln X_7$	−0.202	0.000	−0.264	0.019	−0.466	0.002
Northern Region	$\ln X_1$	−0.040	0.017	0.045	0.169	0.005	0.889
	$\ln X_2$	−0.065	0.033	−0.153	0.002	−0.218	0.000
	$\ln X_3$	−0.099	0.279	0.229	0.332	0.130	0.570
	$\ln X_4$	−0.329	0.000	−0.232	0.118	−0.561	0.002
	$\ln X_5$	0.303	0.002	0.124	0.467	0.427	0.002
	$\ln X_6$	−0.595	0.001	−0.840	0.013	−1.435	0.003
	$\ln X_7$	−0.103	0.293	−0.283	0.108	−0.385	0.138
South Region	$\ln X_1$	−0.029	0.067	−0.015	0.495	−0.043	0.139
	$\ln X_2$	−0.096	0.038	−0.083	0.211	−0.179	0.088
	$\ln X_3$	0.205	0.000	0.396	0.000	0.601	0.000
	$\ln X_4$	−0.212	0.000	−0.0287	0.205	−0.240	0.000
	$\ln X_5$	0.312	0.000	−0.141	0.211	0.170	0.070
	$\ln X_6$	0.192	0.646	−0.399	0.004	−0.206	0.612
	$\ln X_7$	−0.581	0.000	0.064	0.738	−0.517	0.037

4. Conclusions and Implications

4.1. Main Conclusions

This study refers to agricultural data of the main grain-producing areas from 2000 to 2019, uses the spatial autocorrelation analysis to explore the spatial and temporal variation features of the agricultural water footprint based on regional agricultural water footprint assessment, and finally, builds the spatial Dubin model to analyze the influencing factors of the agricultural water footprint in the major grain-producing regions. The main conclusions are listed as follows:

(1) Judging from the time series features of the agricultural water footprint in the major grain-producing regions, it shows a fluctuating downward trend in an inverted N shape. From 2000 to 2019, the agricultural water footprint in the main grain-producing regions was polarized. The internal differences narrowed from an overall aspect, and the low-value provinces and regions were developing rapidly.

(2) Based on the spatial distribution differences of the agricultural water footprint in the major grain-producing regions, the agricultural water footprint is significantly positively spatially autocorrelated from the whole, and it shows high–high and low–low spatial aggregation characteristics in local areas, with a distinct polarization

trend. For example, the northeast region presents low–low aggregation while the Huang-Huai-Hai region presents high–high aggregation. From 2000 to 2019, there was strong spatial dependence, spatial barriers, and path-locking characteristics for the agricultural water footprint in most areas of the main grain-producing regions.

(3) On basis of the influencing factors of the agricultural water footprint in the main grain-producing areas, policy factors, water-saving technologies, social development, economic development, and industrial restructuring could dramatically restrain the increase in the agricultural water footprint. The negative spatial spillover effect of water-saving technologies and industrial structure is strong, and the positive spatial spillover effect of agricultural production and natural factors is powerful, both of which could significantly affect the agricultural water footprint in the adjacent areas.

4.2. Policy Implications

(1) Promoting the development of the agricultural economy with a rational and optimized industrial structure. Industrial restructuring with the proportion of agricultural output value to regional GDP as a proxy variable is helpful to inhibit the agricultural water footprint. It is necessary to control water consumption from the source of agricultural production to realize the sustainable use of agricultural water resources. In the aspect of industrial restructuring, the main grain-producing areas must adjust their internal agricultural cropping structure, decreasing the production of crops with higher water consumption and lower economic value. They also need to adjust the external agricultural industrial structure and vigorously promote other agricultural industries with strong value-added capabilities.

(2) Strengthening the management and control of water resources via a regional-linked management mechanism. The agricultural water footprint in the main grain-producing areas presents high–high and low–low spatial aggregation characteristics, and there is stable spatial dependence for the agricultural water footprint in most provinces. All major grain-producing provinces and regions should improve the agricultural water footprint assessment system, establish regionally linked agricultural water resources management mechanisms, and reform significant methods for agricultural water resources management in order to break the spatial barriers and path locking of the agricultural water footprint, drive the reduction in the agricultural water footprint from low-value areas to adjacent areas, and eventually achieve low-value aggregation of the agricultural water footprint in global areas.

(3) Popularizing water-saving irrigation with complete and efficient water conservancy facilities and technologies. Increasing the proportion of water-saving irrigation areas in arable land, popularizing the application of water-saving technologies, and increasing expenditure on irrigation and water conservancy facilities are all beneficial to curb the agricultural water footprint in major grain-producing regions. The major grain production provinces and regions should provide financial support for the construction of farmland water-saving irrigation facilities and the promotion of high-efficiency water-saving technologies by making full use of the agricultural water-saving project funds provided by the government, and actively guiding the non-governmental funds at the same time. They must enhance the construction of inter-regional and cross-regional farmland water conservancy facilities to establish a "powerful framework" for the development of water-saving agriculture. Meanwhile, they need to positively promote new and efficient water-saving irrigation technologies to "soften the veins" for the development of water-saving agriculture.

In the future, major grain-producing areas need to actively explore regional linkage of water resources management policies with the agricultural water footprint theory, scientifically regulate agricultural water footprint, break the spatial dependence of regional agricultural water footprint, and achieve "low-low" aggregation in the whole region. At the same time, major grain-producing areas should pay greater attention to the R&D,

promotion, and utilization of efficient water-saving technology in the future and accelerate the development of water-saving agriculture to solve the water resource dilemma.

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