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Does Decentralized Food Crop Cultivation Threaten Water-Land-Food Nexus? A Spatial Econometric Analysis

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Abstract: The coordinated development of the Water-Land-Food (WLF) nexus is important for realizing sustainable food production and ensuring national food security. Based on the symbiosis system theory, this study used the Entropy weight TOPSIS method to calculate the WLF nexus of 30 provinces, municipalities and autonomous regions in China from 2003 to 2019. Taking the problem of decentralized food crop cultivation in China as the breakthrough point and using the Panel Tobit Model to empirically explore the threat of decentralized food crop cultivation to the WLF nexus. The results indicated that: (i) The average level of decentralized food crop cultivation index in China for the period 2003–2019 is 2.599 and the growth rate is −12.64%, while the WLF nexus index is 0.317, and the growth rate is 2.42%. Decentralized food crop cultivation showed a fluctuating downward trend in all regions of China, especially in the southwest and northwest regions. However, the WLF nexus index level belonging to the northeastern and Huang-Huai-Hai regions of China is higher, which presents a trend of first decreasing and then increasing. (ii) While the extent of decentralized food crop cultivation threatens the coordination of the WLF nexus in China, it has a time lag. (iii) The decentralized food crop cultivation in non-food producing areas (NFPA) rather than major food producing areas (MFPA) will threaten the WLF nexus. (iv) Compared with the higher WLF nexus index region, the negative effect of decentralized food crop cultivation is more obvious in the lower index region. (v) WFL nexus in the adjacent provinces of China showed regional clustering. Decentralized food crop cultivation will threaten the WLF nexus both in the inner province and adjacent regions. This study argues that the government can use financial subsidies to correct the problem of decentralized food crop cultivation, optimize the level of agricultural outsourcing services, and improve the market for water and land rights, thereby enhancing the WLF system coordination in China.

Keywords: decentralized food crop cultivation; water-land-food nexus; symbiotic system theory; the spatial spillover effect

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1. Introduction

Food security is an important foundation for national security Yu, et al. [1]. The world's major agricultural countries have adjusted and formulated new food development strategies affected by the Corona Virus Disease 2019 (COVID-19), local wars, resource mismatches and extreme weather. Their readjustment and reformulation of food strategies have caused the world food supply chain to become less stable and food security risks to be further accentuated [2]. Thus, improving the food self-sufficiency rate is an effective means of ensuring national food security [3]. While the food self-sufficiency rate of each country has been increasing, it has also brought huge pressure on water supply resources, cultivated land resources, and the ecological environment [4]. The world's demand for water, land, and food resources is projected to increase by 35%, 40%, and 50% respectively in 2030 [5]. As one of the world's largest food consumers, China's total annual water consumption in 2019 was 602.12 billion m^3, including 367.52 billion m^3 for agriculture, accounting for 61.04% of the total water consumption, far more than the sum of industrial water and domestic water [6]. China has 121.72 million hectares of cultivated land, accounting for 12.68% of its national territory. In addition, the shortage and mismatch of water and cultivated land resources among regions are becoming increasingly serious. For example, the cultivated land in the Huang-Huai-Hai region and Northeast China accounts for 44% of the national cultivated land respectively, while the water resources account for only 9% of the national water resources [7]. The mismatch between water resources and cultivated land resources has become a "shortcoming" to restricting food production [8]. The resulting shortage of water resources [9] and scarcity of land resources [10,11] also restrict economic and social development and threaten national stability. This study defines the water-land-food system nexus (WLF nexus) as follows. From the perspective of three dimensions of resource stability, suitability and sustainability, the individual benefits, two-two matching benefits and overall synergistic total benefits of the three subsystems of water resources, land resources and food production are considered comprehensively. How to improve the WLF nexus and ensure sustainable food production under the increasing food demand and limited supply of water resources and cultivated land resources? This is a key issue to be urgently addressed to ensure China's food security and alleviate the pressure on water and soil resources.

The key to improving the WLF nexus is to reduce the input of water and cultivated land resources as much as possible while ensuring the effective output of food and improving the efficiency of food production [12]. Specialized food cultivation is an important means to improve food production efficiency [13]. Nevertheless, the current structure of food cultivation in most Chinese provinces is still relatively fragmented. Fragmented food cultivation may exacerbate the pressure on resources such as water and arable land. Therefore, China's No. 1 Central Document from 2019 to 2020 invariably emphasizes the optimization of food cultivation structure. Interestingly, some scholars believe that diversified food crop cultivation is conducive to improving soil quality and increasing food yield per unit area [14], thereby alleviating the pressure on resources such as water and cultivated land. Accordingly, the goal of this study focuses on examining whether decentralized food crop cultivation threatens China's WLF nexus.

Food in this study refers to grain crops such as wheat, corn, rice, potato and beans. Previous studies on food planting structures have been abundant. Decentralized food crop cultivation is the opposite concept of specialized food cultivation, reflecting the degree of decentralization of food crop cultivation in a region. The more varieties of food crops planted, the higher the degree of decentralization, which is not conducive to mechanized production and raises the labor cost, thus reducing food production efficiency. These studies can be summarized in two dimensions. First, antecedents of the planting structure. Some scholars focused on the perspective of the labor force: Wang, et al. [15] explored its impact on the adjustment of planting industry structure from the perspective of the labor force transfer; Based on her research, Li, et al. [16] argued that rural labor going out to work will lead farmers to adjust their cropping structure. At the same time, Huang and Li [17] analyzed the impact of rising labor prices on the planting structure of major crops in China. Other scholars focus on the perspective of mechanization. Agricultural mechanization is becoming a key factor affecting China's agricultural planting structure. The key reason for "food orientation" is that mechanization is more suitable for food crops [18]. Besides, Chen, et al. [19] indicated that with the development of an agricultural socialized service system, part-time farmers should be promoted to expand food cultivation area through mechanical labor substitution. Second, outcomes of the planting structure. Some scholars have studied the impact of specialized planting on production efficiency. It is believed that the adjustment of planting structure can promote the sustainable increase in food production and improve agricultural productivity [20]. Based on this, Zeng, et al. [21] deeply explored the impact of the two changing directions of crop planting structure change (i.e., crop planting specialization and diversification) on agricultural ecological efficiency. Interestingly, the relationship between planting specialization level and production technology efficiency is an "inverted U" rather than a simple linear relationship [22]. In addition, a few scholars have studied the impact of the internal structure adjustment of the planting industry on the utilization of regional water resources, the total water demand of crops, and the overexploitation of groundwater [23,24].

The core of WLF nexus is the integration of the relationship between solving the problem of resource scarcity, improving production management capacity, and achieving sustainable food production [25]. Among them, water is a necessary element in food production, and cultivated land provides a place for food production [26–28]. Constrained by the traditional way of thinking in resource management [29,30], most existing studies on WLF nexus have focused on three elements: water, land, and food [31–36]. There is still a research gap in the system management of water, land and food [37]. Due to the unique advantages of the method of coordinated measurement of complex systems in terms of resource performance and revealing the internal structure mechanism of resource systems, it is gradually applied to the management of scarce resources [38]. In contrast to simply considering the interactions between resources and production, nexus places more emphasis on the rational transformation of resources within and between complex systems. It is a process of orderly evolution and a virtuous cycle from low to high. nexus focuses on the stability, adaptability, and sustainability between and within systems [39]. Previous studies have used a small number of scenarios and departments to make qualitative or quantitative assessments of the WLF system. Although these studies initially reflect the systemic relationships between water, land, and food but may have overlooked other important drivers [40]. Thus, WLF nexus antecedents remain to be explored [41].

To sum up, in the aspect of constructing the indicator system of WLF nexus, the existing studies mainly independently select indicators for evaluation from three aspects: water resources, cultivated land, and food production, and less consider the coordination of "society-economy-nature" external environment, which cannot reflect the circularity and feedback of the system. A qualitative or quantitative assessment of the WLF system relationship was carried out, but the important driving factors were ignored. And most studies focus on the impact of planting structure on farmers' income, production efficiency and water resources utilization, and few studies on the key role of planting structure in balancing and coordinating a variety of natural resources. Therefore, this study first used "symbiosis theory" to explain the WLF nexus relationship and established a more scientific "water-land-food" nexus index evaluation system based on pressure-state-impact-response (PSIR). Secondly, from the perspective of food cultivation structure, this study empirically explored the potential threat of decentralized food crop cultivation to WLF nexus in China. Thirdly, the regional heterogeneity and spatial spillover effects of decentralized food crop cultivation on WLF nexus in China are analyzed in depth. Finally, this study explored the triggers of WLF nexus and expands the research boundary of decentralized food crop cultivation.

2. Methods and Materials

2.1. Evaluation and Measurement Methods for WLF Nexus

This study measures the WLF nexus index using data from 30 Chinese provinces from 2003–2019. First, this study constructs the WLF nexus index system based on symbiosis theory and the Press-State-Influence-Response (PSIR) model. Then the three sub-dimensions of WLF are measured by entropy weight Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method. Finally, the WLF relationship index is measured by the coupling coordination degree model. The specific indicator selection and calculation methods refer to Li, et al. [42].

2.2. Methods for Measuring Decentralized Food Crop Cultivation

To better quantify the decentralized food crop cultivation (DEFC) in China, the planting area proportion of wheat, corn, rice, potato and beans was selected by referring to Hang, et al. [43] and further calculated by introducing the reciprocal of Herfindahl-Hirschman Index (HHI). As shown in Formulas (1) and (2).

$$DEFC = \frac{1}{HHI} \tag{1}$$

$$HHI = \sum_{c=1}^{n} \left(\frac{F_{c,it}}{Fit} \right)^2 \tag{2}$$

In Formula (2), n = 5, $F_{c,it}$, represents the planting area of food c in area i in year t, where c = 1, 2, 5 refers to wheat, corn, rice, potato and beans respectively; F_{it} represents the total sown area of five major food crops in region i in year t. The higher the *DEFC* value, the higher the decentralized food crop cultivation in the region. On the contrary, the higher the planting concentration.

2.3. Prediction Method of WLF Nexus and Decentralized Food Crop Cultivation

The autoregressive Integrated Moving Average model (ARIMA) is a classical time series prediction method, which refers to the theory and method of establishing a corresponding model for analysis, curve fitting and parameter estimation based on the observed time series data, and then using the model to predict the future [44]. ARIMA model expressions such as Formulas (3) and (4).

$$A(f)(1-h)^d Xt = B(f)\varepsilon_t \tag{3}$$

where X_t is the time series value, f is the backward algorithm of time t, h = αf, α is the coefficient, and ε_t is the error or impact value.

$$A(z) = 1 - \sum_{j=1}^{p} a_j z^j \neq 0(|z| \leq 1), B(z) = 1 + \sum_{j=1}^{q} b_j z^j \neq 0(|z| \leq 1) \tag{4}$$

A (z) is the expansion of $A(f)$; z also represents the lag operator, a_j is the autoregressive coefficient, b_j is the moving average coefficient, p is the number of autoregressive terms, d is the number of differences (orders) made to make it a stationary series, q is the number of moving average terms, j is a positive integer (1, 2, 3, . . .) and the model is abbreviated as ARIMA (p, d, q). Based on the constructed ARIMA model, it is intended to be able to forecast the WLF nexus for 30 provinces, municipalities and autonomous regions in China from 2020–2030.

2.4. Variables Selection

This study combined previous studies to select appropriate dependent variables, independent variables, instrumental variables, and control variables to design the model, and to select appropriate indicators to measure the above variables. Table 1 showed the specific variable indicators and the method of measurement.

Dependent variable: WLF nexus. Referring to Zhi, et al. [45], this study selected 39 indicators related to water, land and food based on the PSRI model from social, economic and natural systems according to a symbiotic perspective and categorized them into three criteria layers: stability, adaptability and sustainability. Using the Entropy Weight TOPSIS method to calculate the evaluation value of the Water-Land-Food subsystem, combined with the coupling coordination model to calculate the WLF nexus, to a certain extent, it can more truly, accurately and reasonably reflect the level of coordinated development among water, land and food in the region. The specific measurement process and results refer to Li, et al. [42].

Table 1. Variables and calculation methods.

Variable Category	Variable	Symbol	Calculation Method	Unit
Dependent variable	WLF nexus	WLF	Referring to Li, et al. [42], Measured by entropy weighted TOPSIS and coupled coordination model	None
Independent variable	decentralized food crop cultivation	Defc	1/Herfindahl index of planting area of wheat, rice, maize, beans and potatoes	None
Instrumental variable	Decentralized food yield	Grte	1/Herfindahl index of yield of wheat, rice, maize, beans and potatoes	None
Control variables	Environmental regulation	Envi	Total investment in environmental pollution control	$\times 10^9$ yuan
	Degree of mechanization	Mach	Total agricultural machinery power/crop sown area	10^2 kW·h/hm^2
	Disaster rate	Disa	Crop affected area/total crop sown area × 100%	%
	Wetland area share	Welt	Wetland area/provincial land area	None
	Rural fixed asset investment	Inve	Investment in fixed assets of rural farm households/number of rural population	10^3 yuan per person
	Technological environment	Tech	Technology market turnover × (total agricultural output value/GDP value)/number of rural employees	$\times 10^4$ yuan per person
	Industrial structure level	Stru	(Value-added of the secondary industry + value-added of the tertiary industry)/gross GDP	km/hm^2

Independent variable: Decentralized food crop cultivation. Most of the previous studies considered the issue of crop planting structure from the perspective of the whole agricultural planting structure [46]. To further refine, this study selects the planting area proportion of wheat, corn, rice, potato, and beans according to Hang, et al. [43], and further calculates by introducing the reciprocal of the Herfindahl-Hirschman Index (HHI), to more scientifically, accurately and reasonably reflect the decentralized food crop cultivation in China from the perspective of internal planting structure of food crops.

Instrumental variable: Decentralized food yield. The instrumental variables method is used in this study to test for possible endogeneity of the model. The change of "Decentralized food yield" is highly related to the endogenous variable "decentralized food crop cultivation", and is independent of the current model's random error term or WLF nexus. Therefore, "Decentralized food yield" is selected as the instrumental variable in this study.

Control variable: According to relevant research results on influencing factors of WLF nexus [47,48], environmental regulation, degree of mechanism, disaster rate, wetland area share, rural fixed asset investment, technical environment, and industrial structure level is selected as control variables of this research model.

2.5. Model Design

Since the WLF nexus (Y) data type belongs to truncated data, the Tobit regression model is used for testing, and the formula is as follows Formulas (5) and (6).

$$Y = \begin{cases} Y^*{}_{it} = \sigma + \alpha_1 D_{it} + \alpha_2 X_{z,it} + \mu_i + \varphi_t + \varepsilon_{it} & Y^*{}_{it} > 0 \\ 0 & Y^*{}_{it} \leq 0 \end{cases} \tag{5}$$

$$Y = \begin{cases} Y^*{}_{it} = \sigma + \alpha_1 D_{i(t-1)} + \alpha_2 X_{z,it} + \mu_i + \varphi_t + \varepsilon_{it} & Y^*{}_{it} > 0 \\ 0 & Y^*{}_{it} \leq 0 \end{cases} \tag{6}$$

In Formulas (5) and (6): Y^*_{it} indicates WLF nexus of region i in year t; D_{it} is the core explanatory variable, indicating the decentralized food crop cultivation of region i in year t; $D_{i(t-1)}$ is the first-order lag term of the core explanatory variable; $X_{z,it}$ represent factors which affecting WLF nexus in region i of year t, $z = 1, 2, \ldots, 7$ represents 7 control variables of environmental regulation, degree of mechanization, disaster rate, wetland area share, rural fixed asset investment, technological environment, industrial structure level; σ represents the constant term of the formula; α represents the coefficient corresponding to each variable; μ_i is the provincial effect that is difficult to observe in each province; φ_t is the fixed effect of time trend; ε_{it} stands for the random error term. Formula (5) is the benchmark model of this study, which is used to test the linear relationship between decentralized food crop cultivation and WLF nexus. In Formula (6), the One period behind decentralized food crop cultivation is added to test the hysteresis of the impact of decentralized food crop cultivation on WLF nexus.

To avoid the influence of the extremum, error terms and other interferences on the estimation results, and describe the phased differences of the influence of decentralized food crop cultivation on WLF nexus at different quantiles, the panel quantile regression model was designed as Formula (7).

$$Y^*{}_{it\tau} = \sigma + \beta_{1\tau} D_{it\tau} + \beta_{2\tau} X_{z,it\tau} + \mu_{i\tau} + \varphi_{t\tau} + \varepsilon_{it\tau} \qquad Y^*{}_{it\tau} > 0 \tag{7}$$

In Formula (7) τ Indicates the quantile. In this study, 10%, 20%, . . . , and 90% are used as quantiles for quantile regression, and the description of other variables is the same as that in Formula (5).

In addition, this study further carries out spatial econometric modeling. First, the global Moran's I index is used to test the spatial autocorrelation of dependent variables, and then the spatial econometric model is selected to analyze its spatial effects.

Moran's I index was first proposed by Moran [49]. Because the measurement method is relatively scientific and simple, it is widely used to test the interaction of dependent variables between regions. The global Moran's I index can be expressed as Formula (8):

$$\text{Moran } I = \frac{\sum_{i=1}^{n}\sum_{k=1}^{m} \omega_{ik}(Y^*{}_i - Y^*{}_{\mathrm{a}})(Y^*{}_i - Y^*{}_{\mathrm{a}})}{S^2 \sum_{i=1}^{n}\sum_{k=1}^{m} \omega ik} \tag{8}$$

where I represent the index, S^2 represents the variance of $Y^*{}_i$, $Y^*{}_{\mathrm{a}}$ represents the mean value of $Y^*{}_i$, and ω_{ik} represents the spatial distance weight matrix, that is, the matrix formed by taking the reciprocal of the spatial distance between i province and k province as the weight, and n and m represent the total number of provinces. The value range of the global Moran's I index is $[-1,1]$. If I is greater than 0, it is a positive correlation, and if I is less than 0, it is a negative correlation. The closer the absolute value is to 1, the stronger the spatial correlation is.

The Spatial Dubin Model (SDM) is used for spatial econometric analysis in this study because the Spatial Dubin Model not only considered the spatial spillover effects of dependent variables and independent variables but considered the impact of random errors and does not need to limit the potential spatial spillover scale. The calculation results are more general [50]. The Space Panel Dubin model is shown as Formula (9).

$$Y^*{}_{it} = \alpha + \rho \sum_{k=1}^{n} \omega_{ik} Y^*{}_{it} + \psi x_{l,it} + \theta \sum_{k=1}^{n} \omega_{ik} x_{l,kt} + \varphi_i + \tau_t + \varepsilon_{it} \tag{9}$$

where, $x_{l,it}$ represents the l variable value of province i in year t, $x_{l,k\mathrm{t}}$ represents the l variable value of province k in year t, l = 1, 2, . . . , 8 refers to decentralized food crop cultivation, environmental regulation, degree of mechanism, disaster rate, wetland area share, rural fixed asset investment, technological environment, industrial structure level. ρ as the coefficient of WLF nexus spatial lag term, it indicates the spatial correlation of WLF nexus among provinces. Ψ refers to the unknown parameter vector of x, indicating the influence direction and degree of each explanatory variable on regional WLF nexus; θ as an explanatory variable, the coefficient of spatial lag term represents the influence coefficient of explanatory variables in other regions on WLF nexus in this region. Φ_i is the provincial fixed effects; τ_t is the time trend effect; ε_{it} stands for random error term.

3. Results and Discussion

3.1. Analysis of Measuring Results of the Decentralized Food Crop Cultivation and the WLF Nexus

The decentralized food crop cultivation and WLF nexus of 30 provinces, municipalities and autonomous regions in China from 2003 to 2019 are compared in different periods (Table 2). We found that the average value of decentralized food crop cultivation at the national level, the MFPA, the main food marketing areas, and the food production, and marketing balance areas showed a downward trend in each period, while the average value of WLF nexus showed a downward trend first and then an upward trend. However, there are great differences between decentralized food crop cultivation and WLF nexus at different periods in each provincial administrative region.

Table 2. Distributional characteristics of decentralized food crop cultivation and WLF nexus.

Producing Area	**Variable**	**Decentralized Food Crop Cultivation**				**WLF Nexus**			
	Year	**2003–2007**	**2008–2011**	**2012–2015**	**2016–2019**	**2003–2007**	**2008–2011**	**2012–2015**	**2016–2019**
	Province/National Average	**2.733**	**2.641**	**2.536**	**2.452**	**0.332**	**0.310**	**0.301**	**0.319**
Main food producing areas	Hebei	2.545	2.327	2.214	2.188	0.346	0.365	0.366	0.394
	Inner Mongolia	3.199	2.869	2.324	2.315	0.321	0.345	0.343	0.367
	Liaoning	2.048	1.817	1.559	1.500	0.377	0.340	0.320	0.325
	Jilin	2.003	1.878	1.608	1.592	0.419	0.355	0.344	0.349
	Heilongjiang	2.987	3.153	2.769	2.936	0.435	0.458	0.482	0.494
	Jiangsu	2.832	2.748	2.723	2.675	0.365	0.390	0.403	0.435
	Anhui	3.467	3.473	3.472	3.241	0.363	0.358	0.371	0.391
	Jiangxi	1.217	1.200	1.213	1.170	0.397	0.306	0.303	0.312
	Shandong	2.424	2.308	2.281	2.188	0.359	0.387	0.411	0.430
	Henan	2.545	2.508	2.484	2.403	0.382	0.377	0.380	0.402
	Hubei	2.818	2.917	2.974	3.031	0.337	0.306	0.313	0.335
	Hunan	1.490	1.378	1.411	1.370	0.372	0.320	0.306	0.308
	Sichuan	4.342	4.259	4.226	4.108	0.312	0.322	0.302	0.313
	Mean value of main producing area	2.609	2.526	2.404	2.363	0.368	0.356	0.357	0.373
food main sales area	Beijing	2.151	1.897	1.890	1.650	0.261	0.240	0.212	0.269
	Tianjin	2.510	2.343	2.196	2.331	0.301	0.246	0.232	0.294
	Shanghai	1.786	2.030	1.966	1.498	0.271	0.283	0.290	0.297
	Zhejiang	1.814	1.779	2.089	2.188	0.376	0.325	0.295	0.301
	Fujian	1.917	1.885	2.015	1.682	0.383	0.314	0.305	0.306
	Guangdong	1.596	1.531	1.509	1.421	0.380	0.351	0.322	0.333
	Chongqing	1.758	1.734	1.771	1.598	0.250	0.210	0.200	0.217
	Hainan	4.107	3.856	3.750	3.571	0.291	0.333	0.280	0.283
	The mean value of main sales area	2.205	2.132	2.148	1.992	0.314	0.288	0.267	0.287
Production and sales balance area	Shanxi	3.075	2.491	2.382	2.131	0.271	0.234	0.238	0.251
	Guangxi	1.975	1.935	2.071	2.159	0.385	0.307	0.274	0.282
	Guizhou	4.447	4.126	3.188	3.912	0.293	0.256	0.184	0.192
	Yunnan	4.363	4.105	3.902	3.501	0.253	0.238	0.236	0.257
	Shaanxi	3.26	3.092	3.097	3.071	0.266	0.254	0.265	0.244
	Gansu	3.298	3.389	3.282	3.147	0.230	0.229	0.229	0.245
	Qinghai	3.682	3.782	3.747	3.588	0.370	0.262	0.249	0.309
	Ningxia	3.766	4.050	3.666	3.153	0.245	0.242	0.238	0.280
	Xinjiang	2.570	2.361	2.285	2.254	0.355	0.339	0.351	0.356
	Mean value of equilibrium region	3.382	3.259	3.069	2.991	0.297	0.262	0.252	0.269

Specifically, the provinces with a rapid decline in decentralized food crop cultivation are Liaoning, Inner Mongolia, Yunnan, Jilin, Hunan, and Hebei, which are mainly concentrated in the MFPA. At the same time, the areas where WLF nexus is rising are also concentrated in the MFPA, mainly including Heilongjiang, Jiangsu, Shandong, Henan, Anhui, Hebei, Inner Mongolia, Hubei, Jilin, and other provinces.

On the contrary, the decentralized food crop cultivation of some provinces in the main food marketing areas even rose in stages, such as Zhejiang, Tianjin, Fujian and Chongqing.

At the same time, the WLF nexus of some provinces in the main food marketing areas decreased, such as Chongqing, Hainan, Beijing and Zhejiang, which is similar to the research results of Wang, et al. [51]. Although the main food marketing areas have a high level of economic development, due to the relative scarcity of cultivated land or water resources, and the decline in the degree of specialization of food cultivation, the WLF nexus continues to decline. The above analysis also showed that WLF nexus tends to decrease in areas where decentr oalized food crop cultivation increases.

3.1.1. Analysis of Trend Characteristics of Water-Land-Food Nexus

According to the calculation results, the mean level of decentralized food crop cultivation in China for the period 2003–2019 is 2.599 and the national average growth rate is −12.64%. The average level of WLF nexus is 0.317, and the average growth rate is 2.42%. The fluctuation ranges of each provincial administrative region are quite different (Figure 1).

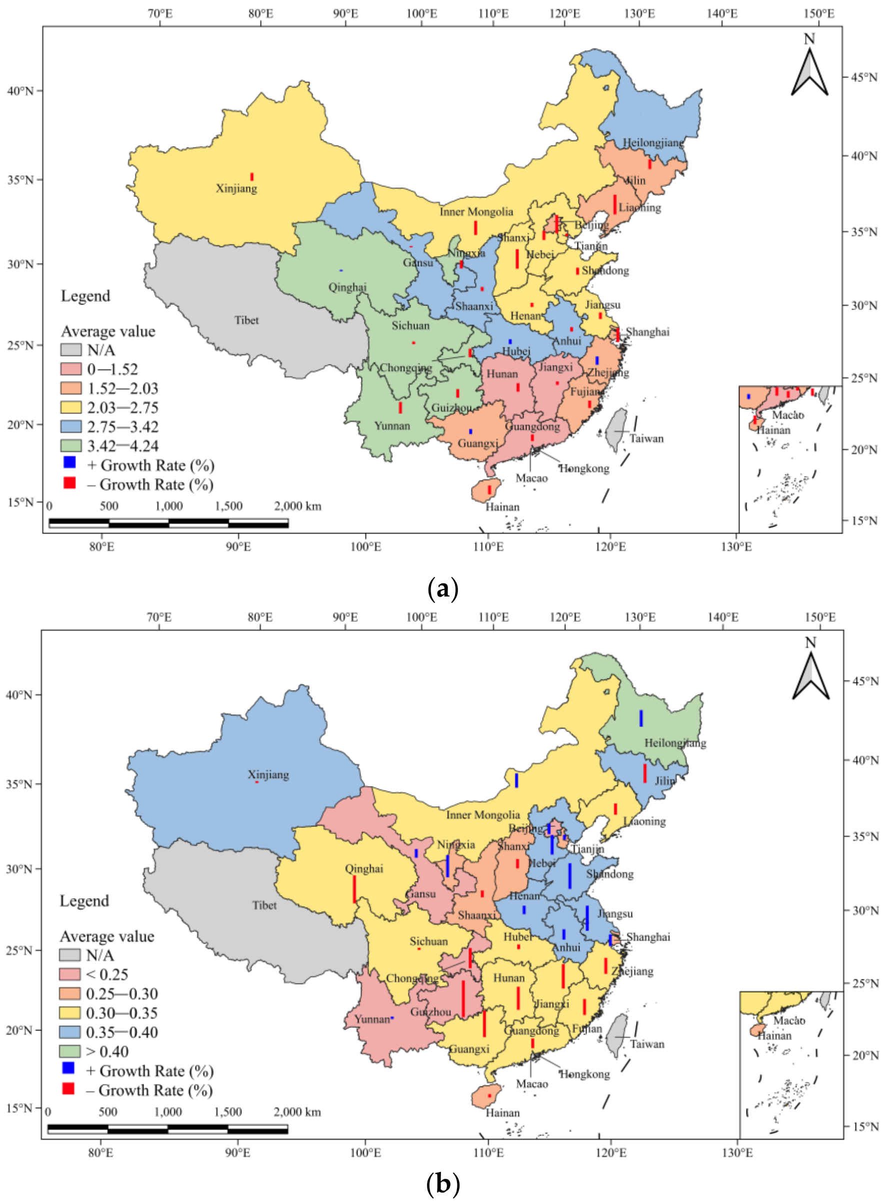


Figure 1. Regional characteristics and growth of decentralized food crop cultivation and WLF nexus, 2003–2019. (**a**) Decentralized food crop cultivation; (**b**) WLF nexus.

From the average level, the decentralized food crop cultivation is lower than the national average, such as Jiangxi (1.201), Hunan (1.417), Liaoning (1.749), Jilin (1.784), Beijing (1.912), Zhejiang Province (1.959), Shandong (2.308), Hebei (2.332), Tianjin (2.355) and other provinces, which are mainly concentrated in the middle and lower reaches of the Yangtze River, Northeast China and the Huang-Huai-Hai region. Regions where WLF nexus is higher than the national average, such as Heilongjiang (0.466), Jiangsu (0.396), Shandong (0.395), Henan (0.385), Anhui (0.370), Jilin (0.370) and Hebei (0.366) provinces, also happen to be in the northeast and the Huang-Huai-Hai region. On the contrary, in the areas where the decentralized food crop cultivation is lower than the national average, Sichuan (4.240), Yunnan (3.991), Guizhou (3.949), Chongqing (3.838), Qinghai (3.699), Ningxia (3.665), Gansu (3.280), Shaanxi (3.138) and other provinces are mainly concentrated in the northwest and southwest regions. WLF nexus is far higher than the national average. Chongqing (0.221), Gansu (0.233), Guizhou (0.235), Yunnan (0.246), Shanxi (0.250), Ningxia (0.251) and other provinces are also located in the northwest and southwest.

From the perspective of growth rate, the areas where the growth rate of decentralized food crop cultivation is lower than the national average growth rate, such as Liaoning (−37.82%), Shanxi (−37.53%), Beijing (−35.32%), Inner Mongolia (−27.37%), Jilin (−18.36%), Hebei (−17.67%), Ningxia (−15.70%), Shandong (−13.54%), Jiangsu (−12.83%) and other provinces, are mainly concentrated in the northeast and the Huang-Huai-Hai region. Regions with higher WLF nexus growth rate than the national average growth rate, such as Shandong (23.61%), Jiangsu (23.12), Ningxia (20.48), Hebei (18.02), Heilongjiang (15.27) and Inner Mongolia (13.23), are also mostly located in the northeast and the Huang-Huai-Hai region. On the contrary, the regions with decentralized food crop cultivation higher than the national average growth rate, such as Zhejiang (16.06%), Guangxi (9.54%), Hubei (9.18%), Qinghai (2.64%), Gansu (−2.39%), Sichuan (−4.96%), Jiangxi (−6.67%), Shaanxi (−7.84%) and Guangdong (−12.81%), are mainly concentrated in the middle and lower reaches of the Yangtze River, northwest and southwest regions. In the regions where the growth rate of WLF nexus is lower than the national average growth rate, Guizhou (−33.76%), Qinghai (−25.75%), Guangxi (−24.60%), Jiangxi (−22.49%), Zhejiang (−14.81%), Guangdong (−8.96%), Shaanxi (−6.22%) and Hubei (−4.41%) and other provinces have deteriorated seriously, and most of them happen to be in the middle and lower reaches of the Yangtze River, northwest and southwest regions.

It can be seen that decentralized food crop cultivation and WLF nexus are always on the opposite side from both the average level and the growth rate, which proves once again that there may be a negative correlation between decentralized food crop cultivation and WLF nexus.

The evolution law of decentralized food crop cultivation in China is shown in Figure 2a,c. Overall, there are two peaks of decentralized food crop cultivation from 2003–2019, and they gradually move to the left. This indicates that the decentralized food crop cultivation in China shows a gradually decreasing trend. Specifically, in 2003, the distribution curve of nuclear density function showed a single peak shape with small intensity but a long span, and the decentralized food crop cultivation in most provinces was between 2.000 and 3.500. From 2003 to 2011, the peak moved to the left, and there was a double peak pattern with a larger intensity and a smaller intensity, indicating that the polarization of the decentralized food crop cultivation in China is gradually emerging. Among them, low-value provinces account for the majority and high-value provinces account for the minority. This may be due to the rapid improvement of food cultivation specialization in most provinces, and a few provinces are unable to follow the adjustment progress. From 2011 to 2019, the peak value of the curve continues to move to the left, showing a double peak pattern with a larger intensity and a smaller intensity and an obvious decrease on the right. It shows that the degree of food specialization in most provinces continues to improve.

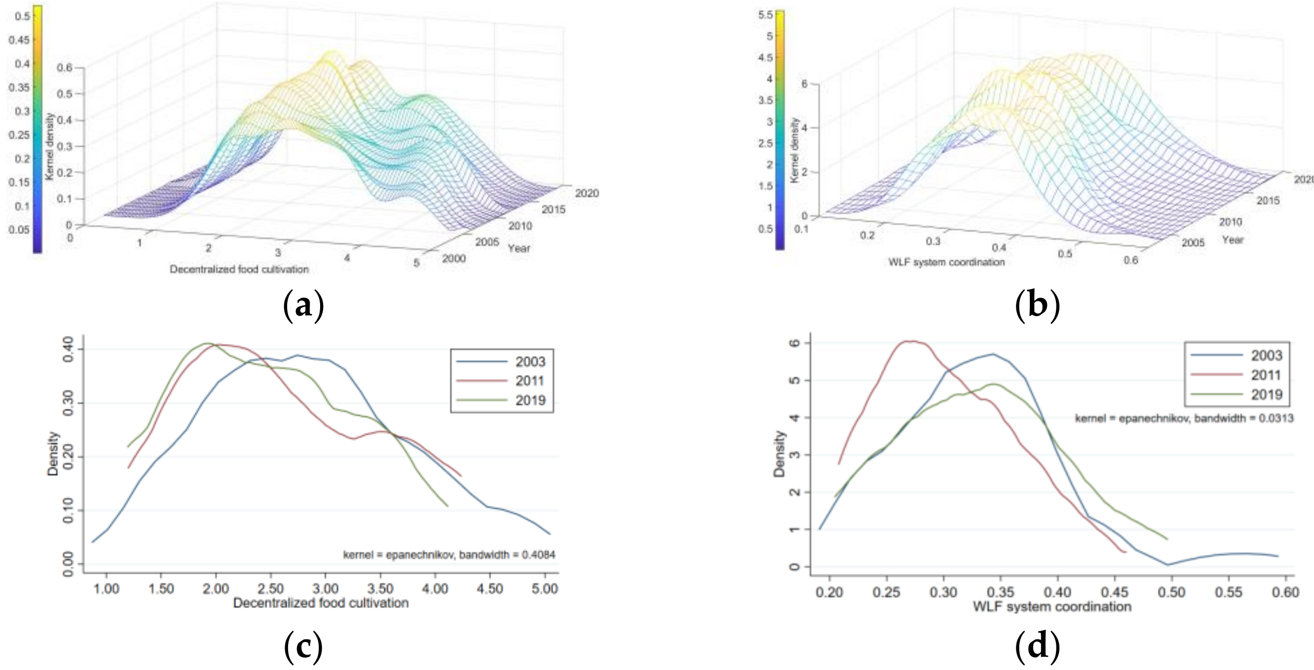
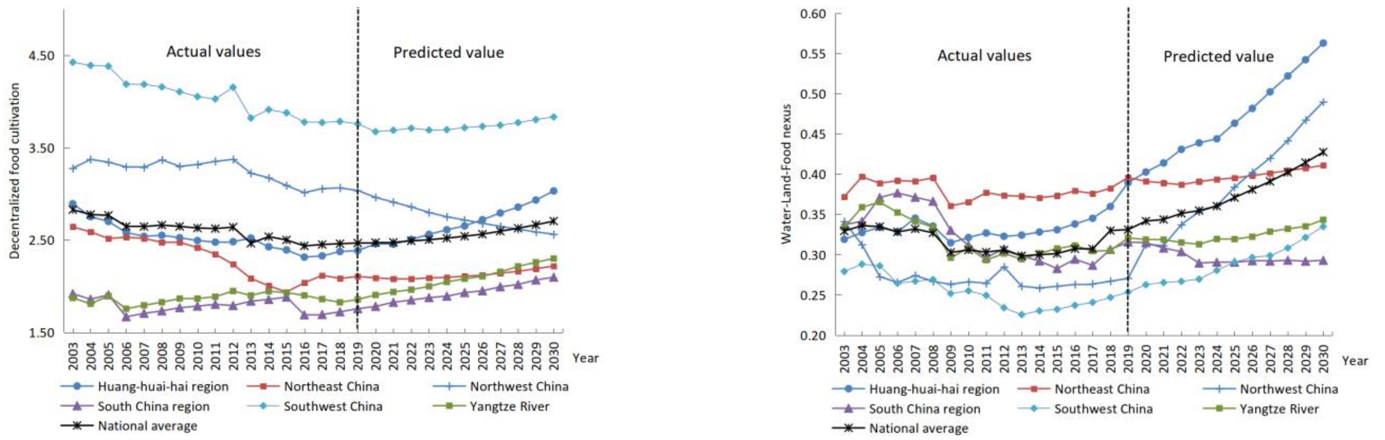


Figure 2. Kernel density estimation of decentralized food crop cultivation and WLF nexus, 2003–2019. (**a**) 2003–2019 decentralized food crop cultivation; (**b**) 2003–2019 WLF nexus; (**c**) Individual years of decentralized food crop cultivation; (**d**) Individual years of WLF nexus.

The evolutionary pattern of WLF nexus in China is shown in Figure 2b,d. Overall, there is a single peak in the WLF nexus from 2003–2019 and it shifts slowly to the left and then rapidly to the right. This indicates that the WLF nexus in China shows a trend of slow decline followed by a rapid increase. Specifically, in 2003, there was a peak with large intensity but a short span in the distribution curve of a nuclear density function, and a very small peak on the right, indicating that WLF nexus in China has polarization. However, in 2011, only one peak with great intensity remained on the left, indicating that the overall WLF nexus in China deteriorated rapidly from 2003 to 2011. From 2011 to 2019, the peak value moved to the right to the 2003 level and the span increased, indicating that China's WLF nexus did not roughly return to the 2003 level until 2019.

3.1.2. Analysis of Trend Characteristics of Decentralized Food Crop Cultivation

From 2003 to 2019, the decentralized food crop cultivation in various regions of China showed a downward trend, while the WLF nexus showed a downward trend first and then an upward trend, and the spatial-temporal differences of regional fluctuations were also obvious (Figure 3). Specifically, the decentralized food crop cultivation in the southwest and northwest regions is at a high level, with a small fluctuation, showing a downward trend as a whole. Among them, Southwest China is at the highest level, decreasing from 4.425 in 2003 to 3.758 in 2019. Northwest China is at the second highest level, decreasing from 3.278 in 2003 to 3.037 in 2019. On the contrary, the WLF nexus in the southwest and northwest regions is at a low level, showing a downward trend first and then an upward trend. Among them, the southwest region is at the lowest level, falling from 0.279 in 2003 to 0.226 in 2013, and then rising to 0.254 in 2019. Northwest China is at the second lowest level, decreasing from 0.314 in 2003 to 0.261 in 2013, with an increase in, and then rising to 0.271 in 2019. This is similar to Han, et al. [52] study. It can be seen that there may be a negative correlation between decentralized food crop cultivation and WLF nexus, which once again provides direction for subsequent empirical tests.



(**a**) (**b**)

Figure 3. Regional characteristics and growth rate forecast of decentralized food crop cultivation and WLF nexus, 2003–2030. (**a**) 2003–2030 decentralized food crop cultivation; (**b**) 2003–2019 WLF nexus.

Judging from the expected growth trend during 2019–2030, the decentralized food crop cultivation in various regions of China will tend to be stable, and there may be a slight upward trend. Among them, South China, the middle and lower reaches of the Yangtze River and the Huang-Huai-Hai region, where the decentralized food crop cultivation is low, are expected to rise to a certain extent, which is expected to be 19.45%, 23.87% and 27.07% respectively. However, Northwest China, which was originally relatively high, may have a downward trend of a certain extent, which is expected to be −15.61%. WLF nexus may have a strong upward trend. Since 2013, the government has focused on ecological and environmental protection, and implemented the concept of sustainable development in food production, resulting in continuous improvement of WLF nexus (Figure 3). Especially in the Huang-Huai-Hai region, where the water pressure for food production is great, policies such as fallow rotation subsidies, scientific and technological empowerment and strict water management have been introduced [53,54], which has made the WLF nexus grow continuously and rapidly. However, due to the rapid economic and social development and increasing population in South China, water and land resources are occupied and a large amount of food is consumed. It is estimated that WLF nexus will decrease by −7.19%.

3.2. Analysis of Empirical Test Results

3.2.1. Decentralized Food Crop Cultivation Affecting the WLF Nexus

According to model 2 in Table 3, decentralized food crop cultivation has a negative effect on WLF nexus (based on Formula (5)). The effect of decentralized food crop cultivation on WLF nexus is significant at the level of 10%, and the coefficient is −0.011. This indicates that for every 1 unit increase in degree of decentralized food crop cultivation, the WLF nexus will decrease by −0.011 units.

Considering that the WLF nexus is influenced by many factors, there may be a problem with omitting variables. There may be an issue of reverse causation between "decentralized food crop cultivation" and "the coordinated of the WLF nexus". Therefore, this study dealt with the endogeneity of the model by using the instrumental variables approach. Since the variation of "Decentralized food yield" is dependent on "decentralized food crop cultivation" variation. Therefore, "Decentralized food yield" is substantially connected with "decentralized food yield" but not with the random error term of the present model or the WLF nexus. The instrumental variable for this study is "Decentralized food yield." In this study, the validity of instrumental variables is first examined, as demonstrated in model 3, where the estimated F value of 35.760 in one stage is greater than the critical value of 10 for the test of weak instrumental variables, and the *p* value of the Wald endogenous test indicates that "Decentralized food yield" is an endogenous variable. Consequently, "Decentralized food yield" is more appropriate as an instrumental variable for "decentralized food crop cultivation". The results of the two-stage regression indicated that the regression coefficient of −0.060 for decentralized food crop cultivation on the coordinated of the WLF nexus was significant at the 1% level, indicating that decentralized food crop cultivation would pose a threat to the WLF nexus's health.

Table 3. Regression results of decentralized food crop cultivation affecting the WLF nexus.

Variable	WLF Nexus			
	Model 1	**Model 2**	**Model 3 (IV-Tobit)**	**Model 4**
Defc		−0.011 * (−1.749)	−0.068 *** (−3.413)	
Lag_Defc				−0.010 * (−1.648)
Envi	0.072 *** (4.841)	0.072 *** (4.840)	0.067 *** (4.011)	0.057 *** (3.949)
Mach	−0.196 (−1.170)	−0.192 (−1.155)	−0.054 (−0.260)	−0.165 (−1.013)
Disa	−0.013 (−0.875)	−0.013 (−0.899)	−0.016 (−0.965)	−0.002 (−0.173)
Wetl	0.002 (0.165)	0.002 (0.159)	0.001 (0.088)	−0.009 (−0.628)
Inve	−0.072 (−1.581)	−0.069 (−1.521)	−0.074 (−1.453)	−0.053 (−1.208)
Tech	0.000 (0.031)	0.002 (0.165)	0.019 (1.313)	−0.000 (−0.027)
Stru	0.006 (0.496)	0.006 (0.450)	0.006 (0.443)	0.009 (0.775)
Time	yes	yes	yes	yes
Ind	yes	yes	yes	yes
One stage F test			35.760	
Wald test	112.080 ***	115.370 ***	35,584.100 ***	113.820 ***
Cons	0.336 *** (18.543)	0.366 *** (14.706)	0.523 *** (9.073)	0.363 *** (15.029)
N	510	510	510	480

Notes: Lag_Defc denotes the first-order lag term of Defc. *** and * represent significant at the 1% and 10% levels, respectively. The number in parentheses is the z value.

In addition, considering that the WLF nexus may have been impacted by decentralized food production in the previous year, the transmission of the influence of decentralized food crop cultivation on the regional WLF nexus may need some duration. For this reason, the first order lagged factor of decentralized food agriculture was introduced to the regression model. Model 4's regression results (based on Formula (6)) indicate that the effect of decentralized food crop cultivation on the WLF nexus's health is significant at the 10% level, with a coefficient of −0.010, indicating that each additional unit of decentralized food crop cultivation will cause the WLF nexus to decrease by −0.010 units the following year. The influence of decentralized food crop cultivation on the regional WLF nexus is seen to have a specific temporal lag.

These results are discussed in the following section. Adam Smith's specialized division of labor theory and the inframarginal analysis of emerging classical economics can explain the improvement of production efficiency brought by specialized food cultivation. This results in less water, land and labor resources being required per unit of food output, reducing the economic cost of food production. At the same time, it also reduces agricultural surface pollution, and carbon emissions, and reduces the ecological cost of food production [21]. Therefore, decentralized food crop cultivation can improve the WLF nexus in the region. On the contrary, decentralized food crop cultivation reduces the regional WLF nexus.

Specifically, decentralized food crop cultivation mainly affects food production efficiency through scale effect, technology effect and competition effect, thus affecting WLF nexus. Decentralized food crop cultivation reduces the input of marginal food production factors (such as machinery, water, land, labor, etc.) through scale effect [55]. At the same time, it helps to promote the division of food production (horizontal division and vertical division) through productive service outsourcing, making factor input more accurate [56]. On the contrary, the decentralized food crop cultivation led to the loss of part of the land due to the increase in plot boundaries and field roads. Additional production factor inputs are required for inter-plot labor. With the increase in the number of plots and boundaries, leakage and evaporation increase, and more inputs such as fertilizer, water and pesticides are wasted [57], thus reducing the stability and sustainability of the WLF system in the region.

Food cultivation specialization can save factor input, increase unit yield, improve food production efficiency [58] and improve the stability and adaptability of WLF system through technical effects. With the passage of specialized food cultivation time, the experience of producers in planting and managing certain crops has been accumulated, which makes field management more scientific [59]. Thus, it is beneficial to improve the utilization efficiency of water and land resources in food production and save or reduce the production factors lost due to the change in production activities. At the same time, concentrated food cultivation makes it easy to derive new technologies for food production and accelerate the speed of technological progress [60]. On the contrary, decentralized food crop cultivation will increase the waste of factor resources, delay the process of technological progress, and reduce the coordination of WLF system.

Decentralized food crop cultivation will reduce food production efficiency and waste production factors through competitive effects. Decentralized food crop cultivation requires producers to select means of production and agricultural machinery according to different food crops and plot conditions, increasing management costs. Moreover, different crops and food crops vie for natural resources such as light, heat, water and land, resulting in strong negative external effects [58]. For example, the growth cycle and habits of different food crops in adjacent plots are different, and the time difference in water, fertilizer, pesticide, irrigation, light and heat input may lead to strong negative external effects.

3.2.2. A Sub-Sample Test of the Impact of Decentralized Food Crop Cultivation on the WLF Nexus

The sample regression results of NFPA are basically the same as the full sample regression (Table 4) and will not repeat (Model 8 to Model 11). However, the regression results of the decentralized food crop cultivation and its first-order lag term in the MFPA on WLF nexus are not significant (Models 5 to 7). This is due to most of the MFPA being plains or basins, with a high level of scale in food production. This has resulted in consistently high levels of food production efficiency and WLF nexus. Considering that the external conditions of food production (such as agricultural machinery and equipment, agricultural infrastructure and food production technology, etc.) are relatively perfect. Every unit of decentralized food crop cultivation increases, the loss of food production efficiency is small, the marginal output loss of water resources, cultivated land resources, pesticides and fertilizers are small too [21], and the threat to WLF nexus is relatively insignificant. On the contrary, the terrain of the NFPA is mostly hilly, plateau and mountainous, and the scale, specialization and intensification of food production are low. The efficiency of food production and the coordination of WLF system are at a low level. In addition, the lack of endowment of other food production factors has caused a large loss of marginal efficiency, which significantly reduces the coordination of WLF system.

Table 4. Regression results of decentralized food crop cultivation and WLF nexus in sub-production areas.

Variable	Major Food Producing Areas			Non-Food Main Producing Areas			
	Model 5	**Model 6**	**Model 7**	**Model 8**	**Model 9**	**Model 10 (IV-Tobit)**	**Model 11**
Defc		−0.006			−0.019 ***	−0.070 **	
		(−0.686)			(−2.653)	(−2.527)	
Lag_Defc			−0.006				−0.020 ***
			(−0.683)				(−2.879)
Envi	0.123 ***	0.124 ***	0.117 ***	0.006	0.003	−0.003	−0.010
	(7.335)	(7.368)	(7.012)	(0.238)	(0.106)	(−0.116)	(−0.422)
Mach	−0.442 **	−0.451 **	−0.393 *	−0.089	−0.104	0.095	−0.089
	(−2.079)	(−2.117)	(−1.898)	(−0.400)	(−0.498)	(0.306)	(−0.442)
Disa	−0.006	−0.005	0.009	0.001	0.001	−0.005	0.004
	(−0.311)	(−0.299)	(0.525)	(0.061)	(0.055)	(−0.202)	(0.210)
Wetl	−0.001	−0.001	−0.001	0.004	0.003	0.004	−0.013
	(−0.042)	(−0.051)	(−0.057)	(0.214)	(0.149)	(0.175)	(−0.687)
Inve	−0.116 *	−0.113 *	−0.124 **	−0.040	−0.027	−0.068	0.001
	(−1.902)	(−1.853)	(−2.111)	(−0.648)	(−0.430)	(−0.941)	(0.022)
Tech	0.024	0.027	0.027	0.010	0.007	0.028	0.003
	(1.355)	(1.481)	(1.521)	(0.619)	(0.413)	(1.382)	(0.165)
Stru	0.005	0.005	0.008	0.023	−0.004	0.003	0.004
	(0.524)	(0.515)	(0.960)	(0.352)	(−0.059)	(0.033)	(0.062)
Time	yes	yes	yes	yes	yes	yes	yes
Ind	yes	yes	yes	yes	yes	yes	yes
One stage F test						20.68	
Wald test	96.820 ***	97.580 ***	95.950 ***	81.170 ***	87.690 ***	11,594.010 ***	90.000 ***
Cons	0.370 ***	0.388 ***	0.392 ***	0.292 ***	0.370 ***	0.509 ***	0.367 ***
	(20.501)	(12.389)	(12.446)	(4.982)	(5.846)	(4.276)	(6.157)
N	221	221	208	289	289	289	272

Notes: Lag_Defc denotes the first-order lag term of Defc. ***, ** and * represent significant at the 1%, 5%, and 10% levels, respectively. The number in parentheses is the z value.

3.2.3. Quantile Test of the Impact of Decentralized Food Crop Cultivation on the WLF Nexus

This study conducted quantile regression with 10%, . . . , and 90% as quantiles to test the robustness of the regression results and analyze the heterogeneity between regions (based on Formula (7)). The results show that the effect of decentralized food crop cultivation on WLF nexus is different at different quantiles. The coefficient of decentralized food crop cultivation at 10% to 90% of the quantiles first remains unchanged and then increases slowly, and the coefficient is stable to negative (Model 12 in Table 5).

It can be seen from Figure 4 that the value of the influence coefficient of decentralized food crop cultivation is relatively stable at the 10–50% quantile, indicating that in regions with low WLF nexus, decentralized food crop cultivation has a stable negative impact on regional WLF nexus. This is because the serious shortage of water resources or cultivated land resources in these regions leads to the mismatch of regional food production, and the coordination of WLF system is low. In addition, the endowment of other factors of food production is not high [61]. Decentralized food crop cultivation has a great impact on food production, resulting in a great loss of marginal production efficiency, thus aggravating the mismatch of the WLF system. However, at the 50–90% quantile, the impact coefficient of decentralized food crop cultivation increases slowly, that means in regions with high WLF nexus, the negative impact of decentralized food crop cultivation on regional WLF nexus decreases slowly with the increase in WLF nexus. This is because the scale, intensification and specialization of food production in these areas are relatively high, and the decentralized food crop cultivation has resulted in a low degree of decline in food production efficiency. This results in lower reductions in food production efficiency due to decentralized food crop cultivation, smaller marginal efficiency losses in resources such as water and arable resources [58], and thus, fewer negative impacts on the WLF nexus.

Table 5. Regression results of the quantile of decentralized food crop cultivation on the WLF nexus.

Variable	Model 12								
	QR_10	QR_20	QR_30	QR_40	QR_50	QR_60	QR_70	QR_80	QR_90
Defc	−0.024 ***	−0.023 ***	−0.024 ***	−0.025 ***	−0.026 ***	−0.025 ***	−0.020 ***	−0.018 ***	−0.010
	(−5.132)	(−6.054)	(−6.901)	(−6.861)	(−7.153)	(−6.279)	(−4.973)	(−4.042)	(−1.120)
Envi	0.105 **	0.151 ***	0.205 ***	0.205 ***	0.196 ***	0.194 ***	0.185 ***	0.155 ***	0.093 **
	(2.200)	(3.246)	(8.056)	(13.315)	(14.642)	(12.750)	(9.603)	(5.874)	(2.315)
Mach	−0.104	−0.159	−0.230	−0.270 *	−0.266 *	−0.330 **	−0.343 **	−0.402 *	−0.477 *
	(−0.690)	(−1.114)	(−1.569)	(−1.891)	(−1.933)	(−2.288)	(−2.070)	(−1.851)	(−1.692)
Disa	−0.040	−0.023	−0.023	−0.041	−0.024	−0.051 *	−0.039	−0.056 *	−0.024
	(−1.381)	(−0.808)	(−0.780)	(−1.528)	(−0.892)	(−1.871)	(−1.369)	(−1.686)	(−0.588)
Wetl	0.013	−0.012	0.006	0.000	−0.012	−0.027	−0.040 *	−0.048	−0.032
	(0.613)	(−0.480)	(0.231)	(0.014)	(−0.543)	(−1.327)	(−1.922)	(−1.570)	(−0.421)
Inve	0.181 ***	0.101	0.111 *	0.077	0.094	0.115 *	0.120	0.302 **	0.730 ***
	(2.622)	(1.409)	(1.696)	(1.253)	(1.606)	(1.668)	(1.243)	(1.967)	(3.217)
Tech	−0.097 ***	−0.068 **	−0.056 ***	−0.057 ***	−0.055 ***	−0.046 **	−0.047 **	−0.067 *	0.002
	(−3.063)	(−2.240)	(−3.057)	(−3.601)	(−3.335)	(−2.423)	(−2.036)	(−1.897)	(0.027)
Stru	−0.100	−0.112 *	−0.112	−0.103	−0.113	−0.116	−0.095	−0.036	0.001
	(−1.488)	(−1.683)	(−1.499)	(−1.205)	(−1.200)	(−1.091)	(−0.689)	(−0.217)	(0.005)
Time	yes	yes	yes	yes	yes	yes	yes	yes	yes
Ind	yes	yes	yes	yes	yes	yes	yes	yes	yes
Cons	0.421 ***	0.450 ***	0.460 ***	0.476 ***	0.501 ***	0.528 ***	0.497 ***	0.456 ***	0.431 ***
	(6.788)	(7.884)	(7.047)	(6.380)	(6.134)	(5.690)	(4.205)	(3.196)	(3.020)

Notes: ***, ** and * represent significant at the 1%, 5%, and 10% levels, respectively. The number in parentheses is the z value.

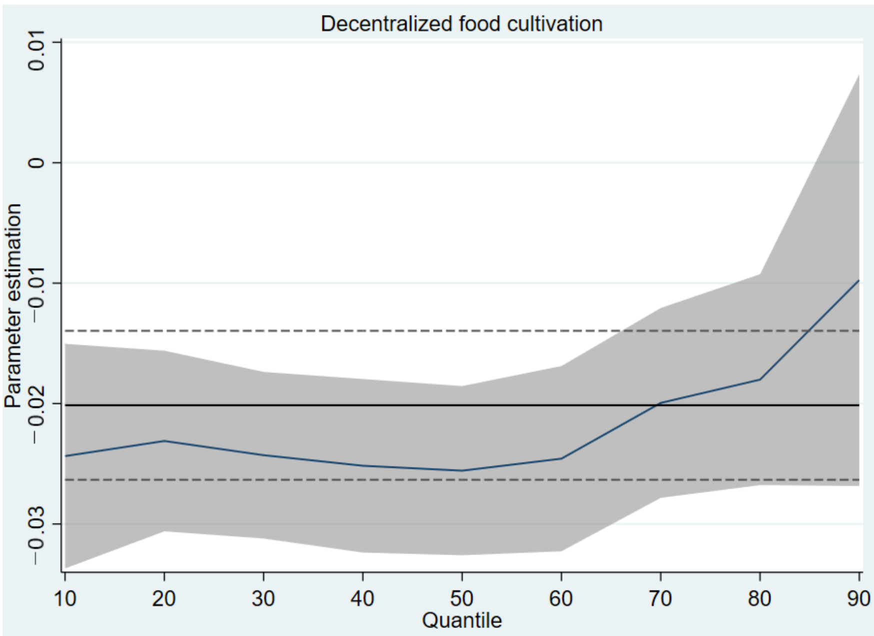


Figure 4. Quantile regression diagram of decentralized food crop cultivation. Note: The blue curve in this figure represents the coefficient of decentralized food crop cultivation at different loci obtained by quantile regression, and the gray area represents the 95% confidence interval of the coefficient.

3.2.4. Spatial Spillover Effect Test

Before analyzing the Spatial Dubin Model (SDM), this study first calculated the global Moran's *I* index (based on Formula (8)) of WLF nexus of 30 provinces, municipalities and autonomous regions in China from 2003 to 2019 by using "proximity weight". The results show that (Table 6) Moran's *I* index for each year passed the significance test, and the coefficients were positive. It shows that there is a strong positive global spatial correlation in WLF nexus.

Table 6. Global spatial Moran index of WLF nexus for 2003–2018.

Year	Moran's *I*	Year	Moran's *I*	Year	Moran's *I*	Year	Moran's *I*	Year	Moran's *I*
2003	0.210 ** (2.110)	2007	0.340 *** (3.037)	2011	0.348 *** (3.156)	2015	0.319 *** (2.914)	2019	0.371 *** (3.329)
2004	0.148 * (1.503)	2008	0.208 ** (1.974)	2012	0.219 ** (2.107)	2016	0.311 *** (2.855)		
2005	0.356 *** (3.180)	2009	0.220 ** (2.100)	2013	0.207 *** (2.553)	2017	0.239 ** (2.247)		
2006	0.300 *** (3.468)	2010	0.213 ** (2.032)	2014	0.320 *** (2.931)	2018	0.169 ** (1.687)		

Notes: ***, ** and * represent significant at the 1%, 5%, and 10% levels, respectively. The number in parentheses is the z value.

Figure 5 shows the spatial distribution scatter diagram of WLF nexus in 2003, 2008, 2013 and 2019. The spatial weighted WLF nexus of most provinces are located in the first and third quadrants of the sample period. That is, the provinces with higher WLF nexus are clustered, and the provinces with lower WLF nexus are adjacent. It can be seen that regions with similar distances have similar WLF nexus levels, and WLF nexus has a certain risk spillover effect. Therefore, the spatial effect should be further considered, and the spatial econometric model should be introduced for analysis to make up for the measurement errors in the model without considering the geographical spatial distribution factors.

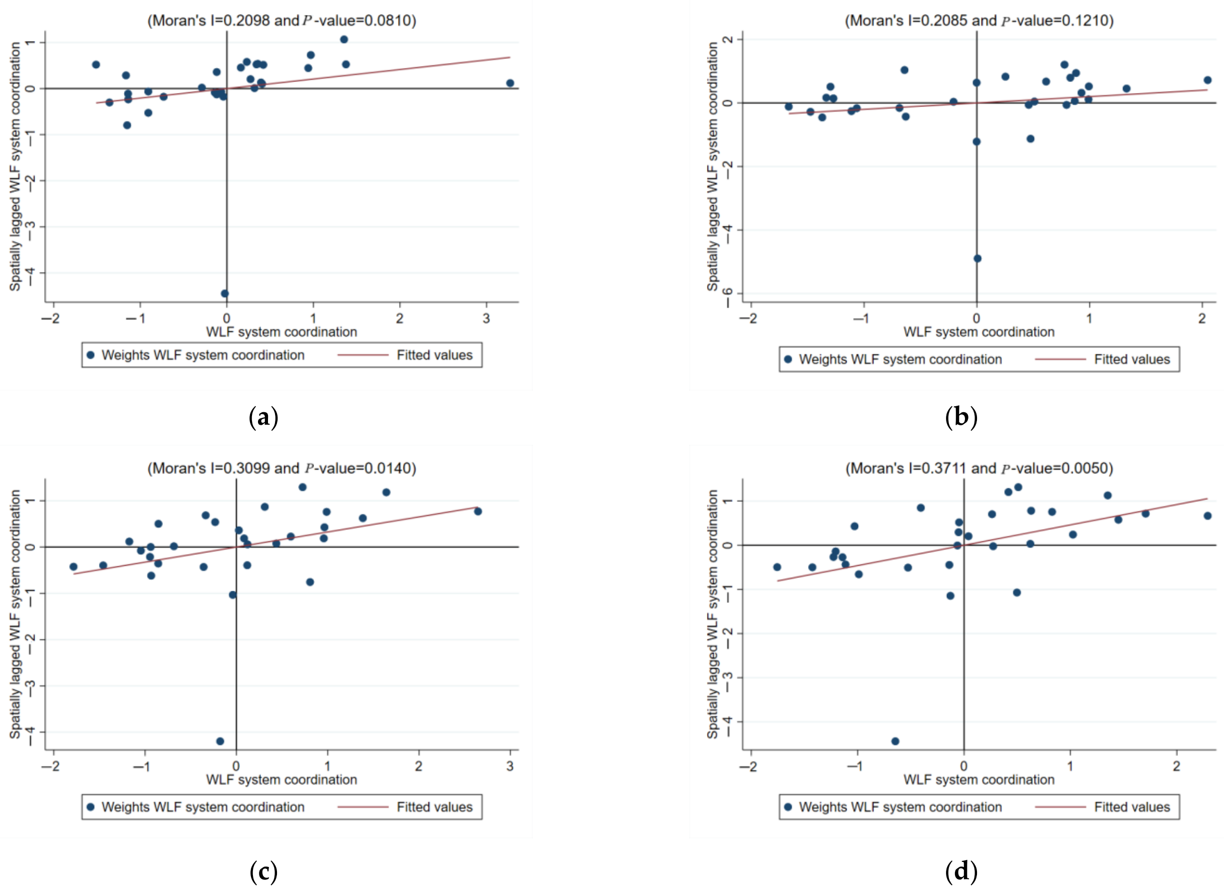


Figure 5. Moran scatter plots of global WLF nexus for different years. (**a**) 2003 WLF nexus; (**b**) 2008 WLF nexus; (**c**) 2013 WLF nexus; (**d**) 2018 WLF nexus.

From Model 13 (based on Formula (9)) in Table 7, it can be seen that in the Panel Spatial Dubin Model (PSDM) measured by adjacent weight, the influence coefficient of the spatial lag term of WLF nexus on WLF nexus ρ It is significant at the 1% level, and the coefficient is 0.345, which proves once again that the WLF nexus among various regions has a positive correlation effect. According to the estimation results of Model 16, it is also found that the impact coefficient of decentralized food crop cultivation in other regions on WLF nexus in this region is −0.017, and it passes the significance test at the 1% level. It can be seen that in the model without considering spatial effects, the negative impact of decentralized food crop cultivation on the regional WLF nexus is underestimated.

Table 7. Regression results of Spatial Panel Dubin Model.

Variables and Tests	**Dependent Variable: WLF Nexus**		
	Model 13		
ρ	**0.345 *****		
Defc	−0.009 ** (−2.179)	ω_Defc	−0.017 *** (−2.914)
Envi	0.118 *** (7.114)	ω_Envi	0.044 (1.377)
Mach	−0.220 * (−1.664)	ω_Mach	−0.486 ** (−2.311)
Disa	−0.061 *** (−2.887)	ω_Disa	0.134 *** (3.696)
Wetl	−0.021 (−0.966)	ω_Wetl	−0.064 (−1.316)
Inve	0.211 *** (3.682)	ω_Inve	−0.084 (−0.683)
Tech	−0.046 *** (−3.253)	ω_Tech	0.008 (0.257)
Stru	−0.048 ** (−2.546)	ω_Stru	0.054** (2.063)
AIC		−1510.491	
BIC		−1434.272	
Observations		510	

Notes: ***, ** and * represent significant at the 1%, 5%, and 10% levels, respectively. The number in parentheses is the z value.

Since the PSDM is not a linear regression, the estimated coefficient cannot directly reflect the marginal effect of decentralized food crop cultivation on WLF nexus. The estimated coefficient should be further decomposed into direct effect, indirect effect and total effect using partial differential method (Table 8). From the decomposition results of direct effect, it can be seen that the direct effect of decentralized food crop cultivation on WLF nexus is significant at the level of 1%, and the coefficient is −0.010, It shows that after considering the feedback effect (That is, the decentralized food crop cultivation that encompasses the region influences the WLF nexus of adjacent areas and in turn influences the WLF nexus of the region.), for every 1 unit increase in decentralized food crop cultivation in the region, the WLF nexus in the region will decrease by 0.010 units. From the decomposition of the indirect effects, it can be concluded that the indirect effect of decentralized food crop cultivation on WLF nexus is significantly negative with a coefficient of −0.028. This indicates that for every 1 unit increase in decentralized food crop cultivation in the region, the WLF nexus in adjacent areas will decrease by 0.028 units. From the decomposition of the total effect, it can be seen that the total effect of decentralized food crop cultivation on WLF nexus is significantly negative with a coefficient of −0.039. This indicates that every 1 unit increase in decentralized food crop cultivation in the region decreases the WLF nexus within the region and adjacent regions by 0.039 units. It indicates that the growth of decentralized food crop cultivation in this region will not only reduce the WLF nexus in this region but also in the adjacent regions. On the one hand, as water resources are highly mobile and are public goods with competing and non-exclusive characteristics, regions with scarce water resources may intensively exploit groundwater resources and overuse surface water resources, taking up water resources in adjacent areas, leading to uncoordinated spillover of WLF systems to adjacent areas [62]. On the other hand, decentralized food crop cultivation leads to a decrease in food production efficiency [58], and food consumption demand forces the province to dispatch food to adjacent areas, disguising competition for resources from adjacent areas. This exacerbates the incoherence of the WLF system in adjacent areas. Conversely, decentralized food crop cultivation can have a demonstration effect on adjacent areas as it generates scale and technological effects that enhance the efficiency of food production and increase the income of producers [63]. Therefore, by reducing the level of decentralized food crop cultivation in adjacent areas, the WLF nexus can be effectively improved.

Table 8. Decomposition results of spatial spillover effect.

Variables	Direct Effect	Indirect Effect	Total Effect
Defc	−0.010 *** (−2.712)	−0.028 *** (−3.487)	−0.039 *** (−4.969)
Envi	0.125 *** (7.812)	0.122 *** (3.061)	0.247 *** (5.484)
Mach	−0.260 ** (−2.060)	−0.809 *** (−2.942)	−1.069 *** (−3.530)
Disa	−0.051 ** (−2.543)	0.161 *** (3.220)	0.110 ** (2.069)
Wetl	−0.028 (−1.180)	−0.105 (−1.463)	−0.133 (−1.523)
Inve	0.213 *** (3.522)	0.001 (0.003)	0.214 (0.979)
Tech	−0.046 *** (−2.936)	−0.013 (−0.290)	−0.059 (−1.099)
Stru	−0.046 ** (−2.465)	0.049 (1.244)	0.003 (0.065)

Notes: Defc. *** and ** represent significant at the 1% and 5%, levels, respectively. The number in parentheses is the z value.

4. Conclusions

The conclusions of this study are as follows. (i) Generally, decentralized food crop cultivation in China for the period 2003–2019 is 2.599 and the national average growth rate is −12.64%. The average level of WLF nexus is 0.317, and the average growth rate is 2.42%. Decentralized food crop cultivation showed a fluctuating downward trend in all regions of China, especially in the southwest and northwest regions. However, the WLF nexus level belonging to the northeastern and Huang-Huai-Hai regions of China is higher, which presents a trend of first decreasing and then increasing. (ii) While the extent of decentralized food crop cultivation threatens the coordination of the WLF nexus in China, it has a time lag. (iii) The regression results for China's regions showed that decentralized food crop cultivation in NFPA rather than MFPA will threaten the coordination of the WLF nexus. (iv) Compared with the higher WLF nexus index region, the negative effect of decentralized food crop cultivation is more obvious in the lower index region. In addition, the WFL nexus in adjacent regions of China showed regional clustering. Local regional decentralized food crop cultivation will threaten the WLF nexus in that region and adjacent regions.

This study adds value to the application in guiding the direction of specialized adjustment of food cultivation structure, alleviating the pressure on resources and the environment, and improving the coordination of China's WLF system. The government can correct the problem of land fragmentation through financial subsidies and market guidance on the one hand. Particularly, subsidies for large-scale and specialized food growers should be increased. Additional attention should be given to the decentralized cultivation of food crops in NFPA. On the other hand, the government should play a key role in promoting agricultural outsourcing services, for example, by providing incentives in terms of policy, funding, and taxation. These initiatives can promote further optimization of the level of agricultural outsourcing services, reduce information asymmetry, and thus promote the process of decentralized food crop cultivation. Finally, the government should improve the market for water and land rights and facilitate a mechanism for the formation of water and land prices that will increase the opportunity cost of water and cultivated land resources for food production. This will in turn force producers to improve the efficiency of water and land resources, thus enhancing the WLF nexus in China.

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