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Telecoupling Effects among Provinces of Cultivated Land Grain Production in the Last 30 Years: Evidence from China

Jingjing Li, Yingbin Feng * and Lei Gu

College of Public Management, Guizhou University of Finance and Economics, Guiyang 550031, China; lijingjing@mail.gufe.edu.cn (J.L.); gulei@mail.gufe.edu.cn (L.G.)
* Correspondence: fengyingbin@mail.gufe.edu.cn; Tel.: +86-18786616879

Abstract: Telecoupling interregional resource interaction based on cultivated land grain production (CLGP) plays a crucial role in ensuring national food security and advancing sustainable socio-environmental and economic development. Based on the provincial panel data of 31 administrative regions in China from 1990 to 2020, we used the spatial and temporal evolution of CLGP and the global Moran index to detect the spatial correlation of CLGP among the provinces in China; we adopted the SDM to study the telecoupling effect of CLGP among the provinces in China and decompose the effect, enabling us to propose policy recommendations for enhancing the telecoupling effect among the provinces. The results are as follows: (1) China's inter-provincial CLGP has shown an increasingly strong telecoupling effect over time, further validating the scientific nature of China's grain production pattern. (2) Cultivated land, irrigation area, the number of agricultural employees, the power of agricultural machinery, the proportion of grain sown, and total grain production have positive "flow" effects on spatial teleconnections between provinces and regions. (3) In terms of the total telecoupling effect, the most significant factor affecting CLGP is the ratio of the area sown with grain to the total area sown with crops. Meanwhile, the area of cultivated land in each region, the irrigated area, the agricultural labor force, the agricultural machinery total power, and the percentage of grain sowing in each region have the most direct telecoupling effect on CLGP. The conduct of the study further fleshes out the empirical research on interregional resource telecoupling linkages arising from resource deployment and utilization.

Keywords: telecoupling; cultivated land grain production; coupling effects; spatial Durbin model

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1. Introduction

Implementing the food security strategy, guarding the bottom line of national food security, and strengthening the foundation of grain is an inevitable requirement for guaranteeing the development of the country in the new era. As the urbanization process continues to advance, the spatial layout of China's grain production has undergone great changes. The "northern transportation of southern grain" has gradually evolved into the "southern transportation of northern grain", and the evolution of the main grain-producing areas, the balance of production and marketing areas, and the main grain-marketing areas have been obvious. However, the contradiction between scientific and technological progress, which promotes steady growth in grain production, and the gradual limitation of cultivated land resources is becoming increasingly prominent. With 7% of the world's arable land resources feeding 21% of the world's population, China's rigid domestic demand for grain is growing; in the uncertain international environment, the rigid domestic demand for grain is increasing. This, coupled with the structural upgrading of the people's growing need for grain consumption, leads to a tense pattern of balance between the supply of and demand for grain in China's region, which will persist for a long period. Based on this, it is of great significance to explore the telecoupling relationship of grain production in the region and accurately analyze the pattern of grain production to further improve the quality of cultivated land use and promote food security.

In research on the quality and quantity changes in cropland utilization and grain production capacity, foreign scholars' research on CLGP mainly focuses on the quantitative prediction of cropland resource endowment [1] and productivity [2], and the research on cultivated land grain productivity mainly focuses on the aspects of yield [3], potential [4], and enhancement path [5]. Domestic research on CLGP mainly focuses on the geographical differentiation of grain production [6], spatiotemporal variations [7], the impact of land use changes on grain production on cultivated land [8], the measurement and correction of regional grain production capacity [9–11], path suggestions to enhance the CLGP, and so on. Domestic and foreign scholars have conducted rich research on cultivated land and its grain production capacity based on remote sensing data and panel data at different scales, based on different time series. However, in the current context of rapid economic development and a shortage of arable land resources, there is limited research on the ecological security conflict. The research ignores the spatial geographic layout of grain output and its correlation with cultivated land grain output elements, and neglects to address the effect of this on China's CLGP yield enhancement. This is necessary to ensure food security, and to ensure that the draw reference value is limited.

Liu et al. explicitly proposed the research concept of telecoupling in 2013 [12]. The coupling relationship between humans and nature is characterized by system evolution, mutual feedback loops, time delay, heterogeneity, and mutation. They created and led the international Coupled Human and Natural Systems (CHANS) project, which emphasizes the interactions between socioeconomic and environmental systems of coupled human–natural systems at long distances, and the need to focus on comparative studies between systems at different scales [13]. Martin-Lopez et al. [14] used the theory of telecoupling to construct a framework for analyzing "cross-scale influence-dependence", considering cross-scale social relations as an inter-regional flow related to ecosystem service assessment; this provides support for the part of telecoupling research that has yet to be recognized. In recent years, as the process of global integration deepens and the ties between countries and regions become increasingly close, a series of socioeconomic–environmental impacts spanning across countries, regions, and scales have emerged [15]. Using this theoretical framework, scholars have conducted in-depth discussions on ecosystem services [16], the "Belt and Road" strategy [17], and energy, and have also made some progress in the area of land use change. Nef et al. systematically examined the intricacies of cross-scale dynamics and the identification of factors contributing to vulnerability across various temporal and spatial scales, ultimately leading to food insecurity in a specific location [18]. This is achieved through a combination of a case study conducted in northern Vanuatu and a broader conceptualization of socioeconomic dynamics within a telecoupling framework. The Netherlands promotes food and land security, as well as socioeconomic development, through the enhancement of technology and the importation of land-intensive products such as food to offset domestic consumption [19,20]. In terms of spatial dimensions, telecoupling involves cross-regional long-distance coupling and cross-scale interactive coupling across multiple nested spatial scales between humans and within the natural coupled system [21]. There are 31 provinces (municipalities and autonomous regions) in mainland China, and the center of gravity of the grain production region has gradually shifted northward. On the one hand, this shift has occurred across the spatial scale and across natural and administrative boundaries; thus, and the regional pattern of grain production has been gradually formed and perfected, with the major grain-producing areas being coupled with the main grain-marketing areas, with a clear distance. On the other hand, human–nature interactions have a decisive impact on distant markets and ecosystems through grain production and marketing across political boundaries.

The core of guaranteeing food security and holding the red line of arable land lies in exploring the complementary capacity that exists for the sustainable production of arable land in each region of the country in the temporal dimension and the capacity of each region of the country in the spatial dimension [22]. Based on the above, this manuscript utilizes the telecoupling perspective, based on the grain productivity of cultivated land, to explore the coupling links between the natural endowment and the socioeconomic factors in different regions, and to clarify the effect of cultivated land grain productivity. The study aims to optimize the allocation of agricultural resources in China's food production, improve the efficiency of grain cultivation, strengthen the foundation of China's food security, and contribute to the case of telecoupling in cultivated land food systems.

2. Connotation Analysis and Research Ideas

2.1. Connotation Analysis

Liu et al. revealed that the human–nature coupling system presents a state in long-distance human activities and large-scale natural processes [23]. That is, the connection gradually extends from neighboring areas to larger distances, evolves from local impacts to global impacts in terms of scale, crosses political or administrative boundaries, and presents multi-nested combinations of spatial scales in the local and global contexts. Telecoupling is a product of the natural continuation of research on human–nature coupling systems.

Natural systems at different distances form interactions between their environments through teleconnections. Human systems at different distances form interactions between different socioeconomic through interaction. Telecoupling occurs when human and natural systems become interconnected and overlap, allowing for socioeconomic and environmental interactions between distant human and natural systems [12,24]. A telecoupling system consists of five interacting parts: system, flow, agent, cause, and effect. Each human–nature coupling system consists of three parts: agent, cause, and effect. These form a complete human–nature telecoupling mega-system through the bonds of interaction between streams. Because of differences in the directions of the flow, the system presents three different states of the system: sending, receiving, and spillover (Figure 1).

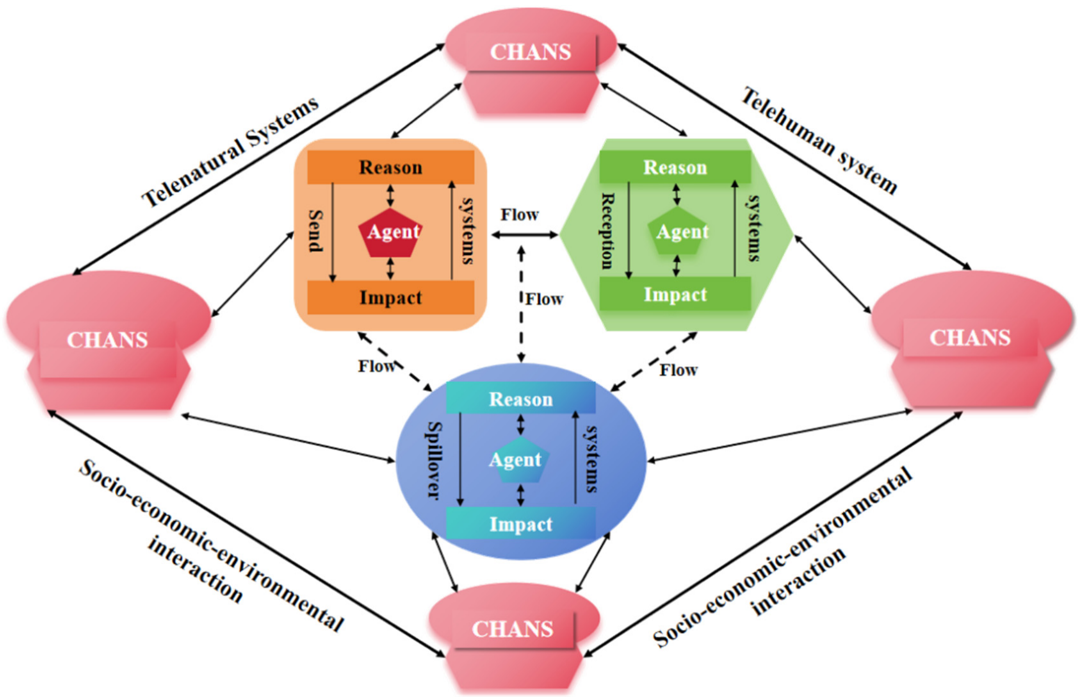

Figure 1. Telecoupling interpretation framework.

Telecoupling achieves the generalization and synthesis of concepts such as teleconnection and the scope of coupling by incorporating environmental interactions between remote natural systems and socioeconomic interactions between remote human systems [25]. The teleconnection dimension, the globalization dimension, and the urbanization dimension form empirical evidence for the analysis of telecoupling. The teleconnection dimension, the globalization dimension, and the urbanization dimension form the empirical evidence for the analysis of telecoupling. In terms of specific regional development, the urbanization process itself can be seen as a type of telecoupling, a historical process of interaction between humans and naturally coupled systems at different spatial distances through flow interactions and inter-system transformations. It is also a process of interaction between economic social and ecological environments between human–natural coupled systems at different spatial distances. These systems reconstruct the teleconnections between urban functions and rural land uses through active bio-flows such as population migration, trade, species dispersal, technology transfer, investment, and transportation. It is important to focus on the impacts of telecoupling interactions between multiple sites on sustainability [23,24]. Exploring the telecoupling effect of "time–space–event" holds immense importance [26], and there is value in studying the cross-regional elements through the carrier of "flow" to promote long-distance human–nature coupling and enable its effects.

2.2. Research Idea

Telecoupling is essentially a complex which is dominated by human beings and the environment, forming a social–economic–natural unity; this aggregates production with living and ecological spaces. Focusing on the rationality of the natural system, the profit of the economic system, and the benefits of the social system [27], one can present macro-to-micro, top–down, and bottom–up coupling chains. In the context of our country, CLGP involves the interactions between the natural environment and the economy and society over long distances and between provincial areas. At the micro level, production relations and productivity in neighboring regions will have a coupling effect on neighboring regions, affecting their choice of grain cultivation, cultivation technology, and cultivation capacity. At the macro level, the grain output of a province has an impact on other provinces; for example, there is an impact of the main grain-producing areas on the main grain-marketing areas. Stable grain production in the main production areas is the only way to sustainably meet the demand for grain in the main grain-marketing areas, promoting the development of a stable economy. Overall, the coupling of various spatial scales between regions undergoes multiple nesting events; spatial coupling is a collection of interconnections between countries and provinces, with telecoupling effects (Figure 2). In China, CLGP is a process of reproduction that involves combining natural resources with the economy and society. The development of cultivated grain production is not only limited by factors such as topography and land quality in natural resources; it is also limited by factors such as regional economic development, agricultural technology, degree of marketization, and policy, which affect the layout of cultivated land production. Based on this, this paper considers three levels of factors: natural resource conditions, agricultural production, and economic development. These are included in the scope of analyzing the telecoupling effect of the CLGP pattern in China (Table 1).

Table 1. Selection of variables for the research subjects.

Indicator Layer	Variable Selection	Expression Symbols
Natural resource conditions	Ratio of damaged area to affected area (damage ratio)	rd
	Irrigation area	lnirra
Agricultural Iproduction	Area of cultivated land in each region	lnland
	Agricultural machinery total power	lntpam
	Fertilizer application amount	lnfer
Economic development factors	Agricultural labor force	lnlabor
	Total area sown with crops divided by grain sown	pgs
	Grain consumption index	GCI

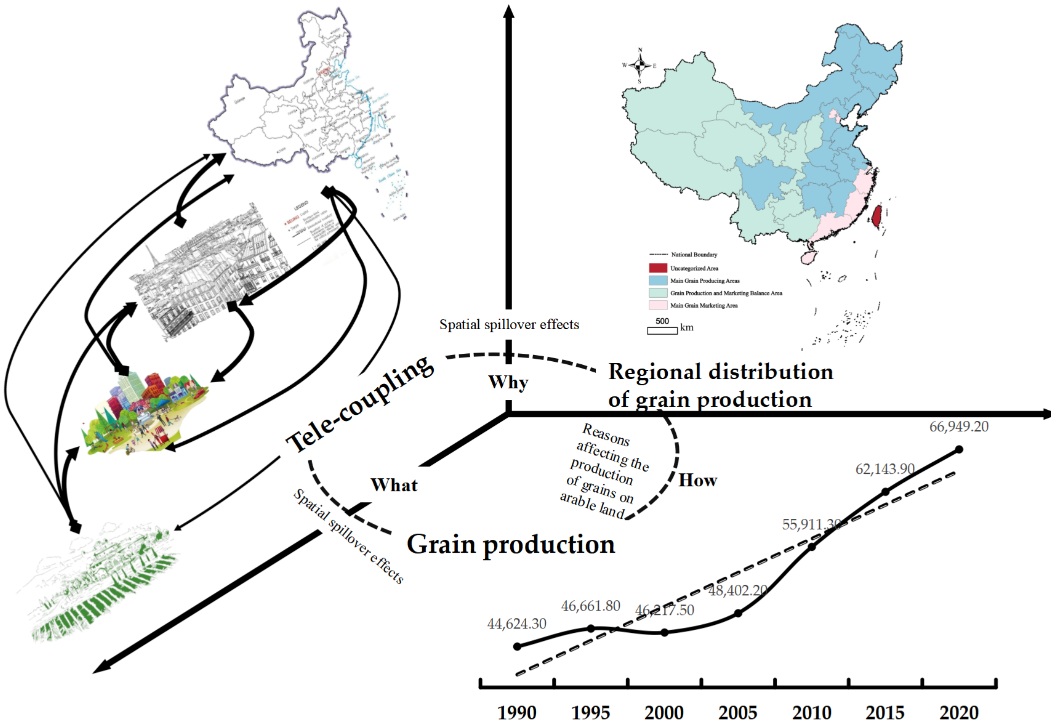

Figure 2. Telecoupling analysis between provinces for CLGP.

In terms of natural resource conditions, in addition to resource endowment, it is necessary to consider climatic factors; extreme weather and local climate changes will affect precipitation, sunshine, land pests, diseases, etc. These are key factors affecting the production of grain crops. In addition, the water resources required for cropland are also an important factor in the layout of cropland and irrigation. Therefore, the ratio of the affected area to the affected area in each region (the hazard rate) and the irrigated area were selected to characterize the natural resource factors of grain production. For agricultural production, the inputs involved in agricultural production generally include land, farm machinery power, fertilizers, etc. Here, land refers mainly to the area of effectively cultivated land; elastic changes in the quality of the cultivated land lead to changes in the cultivated grain yields. That is to say that a reduction in the area of cultivated land inevitably leads to a reduction in the area sown. Fertilizer application amount and agricultural machinery power have a significant impact on cultivated grain production. In certain conditions, the more agricultural machinery power is used, the faster the efficiency and quality of cultivated land are improved, the larger the fertilization area, and the more momentum there is in grain production. Therefore, the cultivated land, the total power of agricultural machinery, and the amount of fertilizer applied in each region were selected to characterize the background indicators of agricultural production. In terms of economic development, as urbanization deepens, the employment opportunities of agricultural labor and non-agricultural labor change according to the regional differences. With a high degree of urbanization, non-agricultural employment opportunities are enhanced, and there is a transfer of labor between industries; thus, it is necessary to take into account the effect of the labor cost of the primary industry. The decline in the labor share of the agricultural industry, without taking mechanization into account, will inevitably lead to a reduction in the area under cultivation, further affecting food production. The economic benefits that can be derived from grain cultivation can be seen in the percentage of the area that has been sown with grain. When the costs and benefits of growing food meet the expectations of the farmers, the area sown with food will steadily increase. It is also necessary to consider the market in which the grain is for sale and the supply and demand for grain. Based on this foundation, agricultural labor, the share of grain-sown area in the total crop-sown area, and the grain consumption index were selected to characterize CLGP's influences.

3. Research Methods and Data Sources

3.1. Spatial Correlation Analysis

According to the first law of geography by Tobler [28], everything is connected to other things, but the correlation between the values of their attributes increases as the spatial distance between them decreases. Therefore, this paper adopts spatial econometrics to find out more about the spatial dependence and heterogeneity of CLGP and telecoupling effects in China. Testing for spatial correlation is the first step in the spatial measurement methodology, which quantifies the degree of spatial dependence of grain production between regions; here, "spatial autocorrelation" and spatial spillovers are judged when observations (high or low) tend to be spatially clustered. Conversely, when presenting a random distribution, there is no spatial autocorrelation.

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

where $\overline{x}$ is the mean value of the observation units of the n constituent study areas, w_{ij} is the spatial matrix used to measure the distance from area i to area j, $\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}$ is the sum of the spatial weight matrices, and n is the sample size. The study area covers 31 provinces, municipalities, and autonomous regions, excluding Hong Kong, Macao, and Taiwan. Therefore, 31 is the value of the variable.

Moran's I values range from -1 to 1, where values less than 0 indicate a negative correlation and values greater than 0 indicate a positive correlation; *Moran's I* converging to 0 is usually considered to be randomly distributed and free of spatial autocorrelation.

3.2. Determination of Spatial Regression Model

In the case of *Moran's I*, the characterization of the spatial dependence problem of the object of study, the spatial regression econometric model measure is usually used to continue the exploration. There are three main forms of spatial measurement models: the spatial Durbin model (SDM), the spatial lag model (SAR), and the spatial error model (SEM). Each of these models exhibits distinct spatial interaction effects, as explained by Fingleton, Le Gallo, and Pirotte [29]. SEM is usually chosen when the error terms of the model exhibit interactions over the space of the study area, with the following general expression:

$$Y = X\beta + \lambda W\mu + \varepsilon,\ \varepsilon \sim N\left(O, \delta^2\right) \tag{2}$$

The explained variable is Y, the explanatory variable is X, the regression coefficient is β, the correlation coefficient of the regression residuals is λ, the random error vector is μ, the random error term is ε, and the weight matrix is W.

When all the independent variables interact spatially and the dependent variable includes a spatial lag operator, SAR is used in the following way:

$$Y = \rho WY + X\beta + \varepsilon,\ \varepsilon \sim N\left(O, \delta^2\right) \tag{3}$$

Unlike the SEM expression, ρ is the coefficient to be estimated for the endogenous interaction effect (WY) of the spatial lag of the dependent variable, characterizing the extent of spatial spillovers.

When the spatial spillovers of the independent and dependent variables in a region are analyzed simultaneously, the spatial Durbin model (SDM) is usually used. This is a more general form of the first two models, with the following expression:

$$Y = \rho WY + \beta X + \theta W_X + \varepsilon,\ \varepsilon \sim N\left(O, \delta^2\right) \tag{4}$$

where the interaction effect between endogenous (WY) and exogenous (WX) is included, θ is the parameter to be estimated for the exogenous interaction effect, and the other parameter settings are consistent with the SEM and SAR models.

The model settings of this research are as follows:

$$\begin{aligned}
\mathrm{lngyld} = & \beta_0 + \rho\sum_{j=1}^{n} \mathrm{W_{it}lngyld_{it}} + \beta_1\mathrm{lnland_{it}} + \beta_2\mathrm{lnirrd_{it}} \\
& + \beta_3\mathrm{lnagla_{it}} + \beta_4 \ln tpam_{\mathrm{it}} + \beta_5\mathrm{rd}_{it} + \beta_6 pgs_{it} + \beta_7\mathrm{lnfer_{it}} + \beta_8 GCI_{\mathrm{it}} \\
& + \theta_1\sum_{j=1}^{n}\mathrm{W_{ij}lnland_{it}} + \theta_2\sum_{j=1}^{n}\mathrm{W_{ij}lnirrd_{ij}} + \theta_3\sum_{j=1}^{n}\mathrm{W_{ij}lnagla_{it}} + \theta_4\sum_{j=1}^{n}\mathrm{W_{ij}} \ln tpam_{\mathrm{it}} \\
& + \theta_5\sum_{j=1}^{n}\mathrm{W_{ij}rd}_{it} + \theta_6\sum_{j=1}^{n}\mathrm{W_{ij}} pgs_{it} + \theta_7\sum_{j=1}^{n}\mathrm{W_{ij}lnfer_{it}} + \theta_8\sum_{j=1}^{n}\mathrm{W_{ij}} GCI_{\mathrm{it}} + \varepsilon
\end{aligned} \tag{5}$$

where gyld is the explained variable, $\mathrm{W_{it}}$ is the element in the spatial weight matrix, $\mathrm{W_{it}}$gyld represents the spatial correlation between food production in each region, and $\mathrm{W_{ij}rd_{ij}}$ and other spatially lagged dependent variables show the degree of influence by neighboring regions. Irrd, etc., are control variables; $\beta_0 \sim \beta_8$ is the regression coefficient of the variable; $\theta_1 \sim \theta_8$ is the spatially lagged regression coefficient of the variable; $\mathrm{W_{ij}}$ is the geographic distance weight matrix; i is the region; t represents the time series. This study involves two types of spatial weight matrices, namely the geographic distance weight matrix based on latitude and longitude, and the economic distance matrix based on the GDP of various regions in China.

The spatial econometric model needs to be integrated with the actual study area and passes the likelihood ratio test (LR), the Lagrange multiplier test (LM), and the Wald test. Two hypotheses are proposed here. H1: SDM can be simplified to spatial lag model SAR; if prob>chi2 is significant, then the original hypothesis is rejected and SDM is chosen. H2: SDM can be simplified by simplifying to spatial error model SEM; if prob>chi2 is significant, then the original hypothesis is rejected and SDM is chosen.

3.3. Data Sources

The data utilized to estimate the model in this manuscript were derived from panel data encompassing 31 provinces, municipalities, and autonomous regions in mainland China spanning from 1990 to 2021. Among them, data on the grain yield, the sown area of farm crops, agricultural machinery power, and chemical fertilizer application were derived from the China Rural Statistical Yearbook (1991–2021). Data on the agricultural labor force and the grain consumption index were derived from the statistical yearbooks of 31 provinces, municipalities, and autonomous regions for the years 1991–2021. The ratio of the affected area to the affected area in each region (the hazard rate) was calculated based on relevant data from the China Rural Statistical Yearbook. The area of cultivated land in each region was collected and summarized based on the National Land Use Change Survey Report and the statistical yearbooks of each province and city. In order to calculate the cultivated land area, interpolation was used due to the absence of data for a part of it. At the same time, to ensure that the data passed the smoothness test, the time series data were logarithmized. Furthermore, in the process of realizing the spatial visualization of the study object, only the study areas located in mainland China with data attributes have been depicted. The spatial visualization of non-study areas has been illustrated in another map of China that does not incorporate data classification and displays the grain production zoning of cultivated land.

4. Analysis of Results

4.1. Evolution of Spatial and Temporal Patterns of CLGP

China's grain production has experienced fluctuating overall growth over the past 30 years. CLGP steadily increased from 4.46×10^8 t to 5.05×10^8 t million tons from

1990 to 1996. There was a sustained decline in grain production between 1997 and 2003, but from 2004 onwards, 14 years of production increases were achieved. It is worth noting that 2018 saw a reduction in grain production from 2017 by 0.56%, but growth was again realized by 2020. From the point of view of the growth of the region, over the past 30 years, Nei Mongolia Autonomous Region saw the largest increase of 276.58%. Northeast Heilongjiang Province showed the second largest growth period, from 2.31×10^8 t in 1990 to 7.55×10^8 t million tons, with a growth rate of 226.09%. Through ArcGIS, Natural Breaks was used to segment China's grain output of cultivated land between 1990 and 2020 (Figure 3), which shows that China's annual grain output has gradually increased. In 1990, the high-grain-yielding areas were Shandong Province, Jiangsu Province, Hunan Province, Sichuan Province, and Henan Province. Meanwhile, in 2000, the fifth level of high-grain-yielding areas included Shandong Province, Henan Province, Jiangsu Province, and Sichuan Province. In 2010, the fifth level of high-grain-yielding areas included Shandong Province, Hunan Province, Jiangsu Province, and Henan Province. In 2020, the fifth level of grain production areas changed to Heilongjiang Province, Henan Province, and Hunan Province; the high-grain-production areas gradually shifted to North and Northeast China. In addition, the analysis shows that grain production in northern regions such as the Nei Mongolia Autonomous Region and the Northeast Plain has increased significantly due to the collectivization of cultivated land and the improvement in land quality. In areas in the southern region, such as the Pearl River Delta region, we can observe the deepening of the urbanization process with the formation of a hub of development in the secondary and tertiary industries; here, the supply of food to the south from the north has fed the situation. The northeastern region has witnessed a change from the previous situation, where it was the "Great Northern Wilderness"; this region has become one of the most important regions in China for stabilizing the "ricebowl".

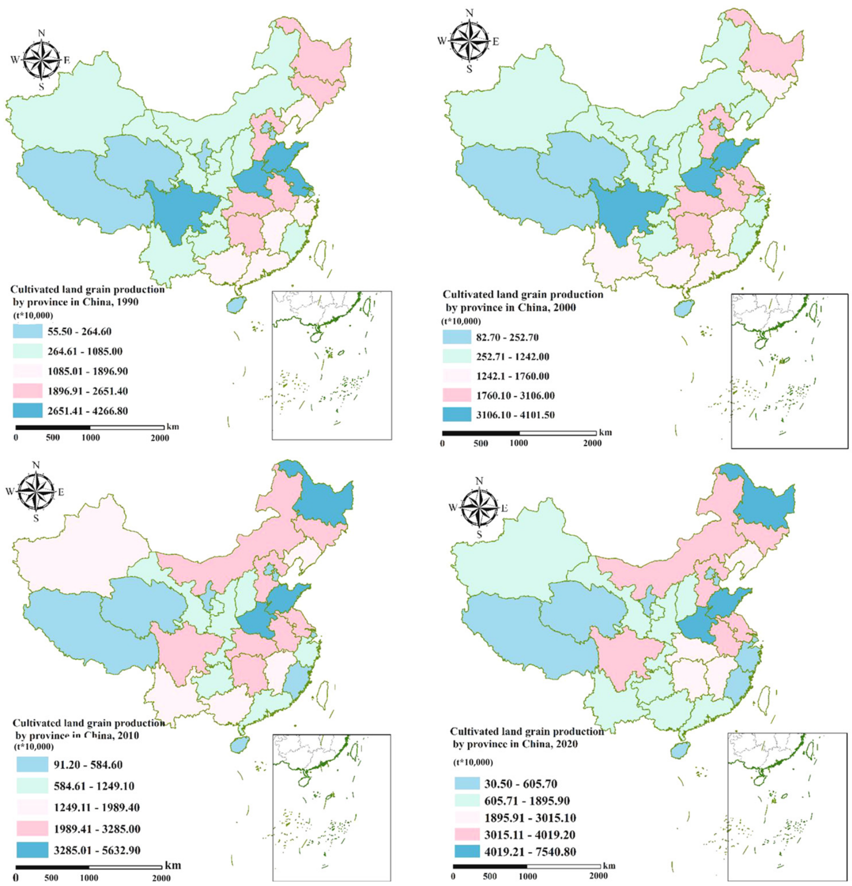

Figure 3. Spatial distribution of grain production on cultivated land in China (1990–2020).

We can further explore the pattern of CLGP in China through an analysis of the spatial center of gravity standard deviation ellipse (Figure 4). It is observed that China's grain production in the area has been shifting towards the northeast, this has particularly been the case since the 21st century; the standard deviation ellipse is progressing at a faster pace. Furthermore, the coverage of the northern region within the range is steadily growing, confirming the scientific validity of China's grain production formation pattern. The population density in the northern part of China is lower than that in the southern part of the country, and the dependence of the main grain-marketing areas, such as the Beijing and Guangdong Provinces, on the main grain-producing areas has gradually become apparent. Telecoupling relationships have emerged between the main grain-producing areas mainly in the north and the main marketing areas or even the basic equilibrium areas; the relationships of their effects needs to be explored on a spatial scale.

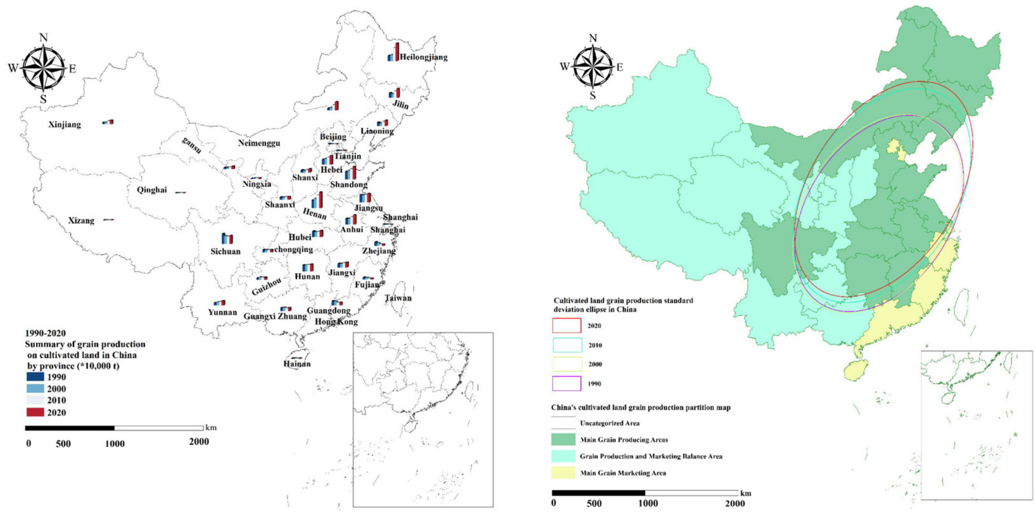

Figure 4. The trend of the center of gravity shift in China's grain production (1990–2020).

4.2. Measurement of Telecoupling Effects of CLGP

4.2.1. Spatial Correlation Test

Using stata17.0 to measure the global Moran' I index of China's CLGP, the results show that it is greater than 0, and its P-value has a significant feature at the 10% level; these results indicate that there is a spatial spillover effect in China's interprovincial grain production during the 31-year period from 1990 to 2020. The closer the neighboring of the provinces and regions, the stronger the correlation is. It should be noted that the fluctuation of the Moran' I and other spatially related significant indices should be considered as a result of uncontrollable natural factors, regional socioeconomic development orientation, and policies. However, the gradual increase in the index value further indicates that the layout and production of CLGP are becoming more and more stable. The prerequisite for conducting the test of dynamic spatial spillover effects is to conduct the *Morans' I*, which determines the spatial correlation of CLGP in China in order to carry out the next step of measuring the spatial telecoupling effects of grain production.

4.2.2. Analysis of Telecoupling Effects

(1) Determination of the SDM. The statistical quantities of the non-robustness of the observations of grain production in China show that both the spatial lag model and the spatial error model are significant, and the choice of SDM is reasonable and requires the LR and Wald tests further. Assuming that the SDM can be simplified to the SAR, the original hypothesis is rejected, and SDM is chosen if prob>chi2 is significant. Assuming that the SDM can be reduced to an SEM, if prob>chi2 is significant, then the original hypothesis is rejected and SDM is selected. The results show that the SDM cannot be degraded to an SAR or an SEM. Based on the Wald test results, it was found that the Wald test statistic was

significant at the 5% level. This implies that choosing the SDM over the SEM and SAR was more favorable. As a result, the SDM was selected to conduct the spatial telecoupling test for China's CLGP. Hausman test for fixed and random effects based on the SDM and the robust Hausman test *p*-value is 0.00, so the original hypothesis is strongly rejected, and the fixed-effects model is used. The estimated parameters under fixed effects were finally chosen to be more effective for spatial telecoupling effect analysis.

(2) Factors affecting telecoupling effects. As can be seen from Table 2, the spatial autocorrelation coefficient is positive, which further illustrates that there is a spatial clustering effect of grain output among provinces in China, and telecoupling effects are evident. The coefficients of the main explanatory variables on the region (Main) show that there is a negative correlation between the ratio of the damaged area to the affected area and fertilizer application and grain output; the lower the disasters, the higher the grain output. Here, the application of fertilizer is overused to a certain degree, which will similarly affect the regional grain output; consequently, the spatial pattern of grain output has changed. The grain consumption index, which is not significant in this model, shows that the grain consumption in our population pattern belongs to the consumption of necessities. The growth or decrease in the price of food consumption depends on the grain production of the current year or the previous year. Here, people's production and the demand for food are stable; they will not be affected by the increase in the price of the demand for the reduction in the amount of demand. Cultivated land, irrigated land, the number of agricultural laborers, the power of agricultural machinery, and the share of grain sowing are significantly and positively correlated with total grain production. They have a significant impact on total grain production and the pattern of grain production.

Table 2. Results of SDM estimation.

VARIABLES	Main	Wx	LR_Direct	LR_Indirect	LR_Total
lnland	0.335 ***	−0.128 *	0.334 ***	−0.057	0.277 ***
	(−9.35)	(−1.76)	(−9.06)	(−0.66)	(−2.91)
lnirra	0.218 ***	−0.113 ***	0.213 ***	−0.077	0.136 ***
	(−7.96)	(−2.71)	(−8.23)	(−1.61)	(−2.88)
lnlabor	0.072 **	0.172 ***	0.085 ***	0.229 ***	0.314 ***
	(−2.53)	(−3.25)	(−3.11)	(−3.75)	(−4.50)
lntpam	0.278 ***	−0.052	0.278 ***	0.016	0.294 ***
	(−12.07)	(−1.21)	(−12.56)	(−0.33)	(−5.96)
rd	−0.068 **	0.01	−0.068 **	−0.011	−0.079
	(−2.05)	(−0.15)	(−2.11)	(−0.14)	(−0.86)
pgs	0.613 ***	0.194 *	0.634 ***	0.421 ***	1.055 ***
	(−14.67)	(−1.86)	(−15.57)	(−3.59)	(−8.55)
lnfer	−0.016 ***	0.017	−0.016 ***	0.015	−0.001
	(−2.98)	(−1.28)	(−2.62)	(−0.93)	(−0.03)
GCI	0	0	0	0	0
	(−0.12)	(−0.75)	(−0.25)	(−0.74)	(−0.81)
Spatial			0.228 ***		
rho			(−5.37)		
Variance			0.017 ***		
sigma2_e			(−21.84)		
R-squared			0.936		

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

In addition, the estimated coefficients of Wx for the area of cultivated land in each region, the irrigated area, the agricultural labor force, and the ratio of area sown with grain to the total area sown with crops all pass the significance test from the spatial lag term. These variables have an impact on the transformation of grain yield patterns through telecoupling effects (Wx represents the coefficient of spatial spillover of explanatory variables to other regions). Among them, the agricultural labor force has the highest significant coefficient in space, which can be seen as the spatial mobility of the rural labor force produces spillover benefits, forming a closer telecoupling interaction. The current impact of fertilizer application amount on cultivated land and food is limited, as it influences the quality and yield of the land and has a minimal effect.

4.2.3. Decomposition of Telecoupling Effects

According to Lesage's research [30], if the spatial correlation coefficient of the explanatory variables is not zero, then the spatial effect of the decomposition of the explanatory variables is required. By combing the literature [31], we found that the factors influencing the changes in the telecoupling effect arising from the pattern of food production in China are decomposed into direct, indirect, and total effects.

The direct effect analysis in Table 2 shows that, among the factors involved in influencing the telecoupling of CLGP in China, the area of cultivated land, the irrigated area of cultivated land, the number of people in the agricultural labor force, the power of agricultural machinery, and the percentage of grain sowing are all significant through the condition of the 1% level. Also, the ratio of the damaged area to the affected area is significant through the 5% level, which is a significant performance of the interaction effect on the CLGP in China. The analysis reveals that the ratio of grain sown to the total sown area in the direct effect is the factor that affects the total grain yield the most, i.e., under certain conditions, the size of grain-sown area directly affects the amount of grain yield in the region, and the remote area adjusts the area of grain sown in the region in response to the supply and demand of grain. In addition, the following order can be seen: cultivated land > agricultural machinery power > irrigated area > agricultural labor > disaster ratio.

The indirect effect shows that the agricultural labor force and the ratio of area sown with grain to total area sown with crops pass the significance test, and both are significant at the 1% level. This is due to the gradual formation of China's cultivated land pattern; the main production areas, the production and marketing balance area, and the main marketing area basically tends to be balanced. Also, the regions have gradually formed a clear and prominent strength, becoming the center of gravity of the development of the region. Each of them synergize to help the country's development. It is worth noting that, through the indirect benefits of spatial telecoupling of grain, the share of grain sown has a positive effect on the surrounding provinces or surrounding cities. This is closely related to the general background of China's successive years of increased grain production and the general policy of "CHINESE RICE FOR CHINESE PEOPLE".

From the telecoupling total effect, the ratios of the area sown to the cultivated land, the agricultural labor force, the total area sown with agricultural machinery, and the grain sown with crops are significant and positive at the 1% level in each region. The ratio of area sown with grain to the total area sown with crops shows a higher total effect than other factors, indicating that the center of gravity of CLGP will be shifted to such provinces and regions with a large ratio of area sown with grain total area sown with crops, which will eventually form the grain production pattern. It is worth noting that the factor of fertilizer application amount is not significant in the overall effect in space and remoteness, and is only significant in the direct effect, which shows that fertilizer application only affects the CLGP in the proximate region.

4.3. Robustness Test

To examine the robustness of this empirical study, an empirical test was conducted using the economic spatial distance matrix in place of the geographic adjacency matrix (Table 3). The results showed that the significant degree of the model and the direction and size of the role of key variables basically remained consistent. It is evident that the spatial telecoupling impact of grain production in China's cultivated land is both strong and significant. Furthermore, factors like the size of the cultivated land and the agricultural workforce consistently play crucial roles in shaping the patterns of grain production.

Table 3. Estimated results of the SDM for the economic distance spatial matrix.

VARIABLES	Main	Wx	LR_Direct	LR_Indirect	LR_Total
Lnland	0.355 ***	0.520 ***	0.346 ***	0.424 ***	0.771 ***
	(−9.86)	(−4.1)	(−9.39)	(−3.8)	(−6.39)
Lnirra	0.185 ***	−0.156	0.187 ***	−0.162 *	0.025
	(−7.8)	(−1.57)	(−8.17)	(−1.85)	(−0.28)
Lnlabor	0.146 ***	0.486 ***	0.139 ***	0.410 ***	0.550 ***
	(−4.66)	(−4.28)	(−4.74)	(−4.04)	(−4.85)
Lntpam	0.210 ***	−0.051	0.211 ***	−0.074	0.137 **
	(−9.58)	(−0.72)	(−9.76)	(−1.19)	(−2.21)
Rd	−0.045	0.242 **	−0.049	0.218 **	0.169
	(−1.32)	(−2.19)	(−1.52)	(−2.2)	(−1.57)
Pgs	0.710 ***	−0.028	0.715 ***	−0.116	0.600 ***
	(−17.54)	(−0.37)	(−17.8)	(−1.59)	(−7.65)
Lnfer	−0.012 **	0.013	−0.012 **	0.012	0
	(−2.09)	(−0.67)	(−2.08)	(−0.72)	(−0.02)
GCI	0	0	0	0	0
	(−0.80)	(−0.66)	(−0.86)	(−0.61)	(−0.86)
Spatial			−0.151 **		
Rho			(−2.31)		
Variance			0.018 ***		
sigma2_e			(−21.88)		
R-squared			0.854		

Note: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

4.4. Further Analysis

With the help of the economic distance matrix, the telecoupling effect was tested in four types: the main grain-producing area, the main grain-marketing area, the grain production and marketing balance area, and a combination of the main grain-producing area and the main grain-marketing area (Table 4). The results show that, in the direct effect, the area of cultivated land, the irrigated area, the agricultural labor force, and the ratio of the area sown with grain to the total area sown with crops are all significant at a 1% level in each type; meanwhile, the fertilizer application and the grain consumption index are not significant. It is worth noting that the ratio of grain sown with the total area sown with crops shows a significant negative telecoupling effect, which can be seen in the main marketing area due to economic, social, and geographic factors. The ratio of area sown with grain to the total area sown with crops gradually decreases, and the demand for grain generation in remote areas gradually expands; here, the telecoupling effect is increasingly obvious.

In the telecoupling indirect effect of CLGP, the influence of factors affecting the balance of CLGP and marketing area—including each area of cultivated land, the agriculture labor force, and the ratio of area sown with grain to the total area sown with crops—is significant at the 1% level; the irrigated area is significant at the 5% level. GCI in the indirect effect produced by the main grain-marketing area is significant at the 5% level, and the correlation coefficient is negative; it can be seen that the main marketing area of the grain consumption index—by the effect of the remote region—is greater in the economic expenditure of the presentation of the necessities of the consumer price fluctuations. The impact of the main grain-marketing area of the population of the consumption expenditures shows an indirect spillover effect. In addition, the main marketing area and the main production area combination, with the type of total power of agricultural machinery and agricultural labor force is significant at the 1% level. Thus, the remote spillover effect of the main marketing area and the main production area between the agricultural labor force and agricultural machinery power is obvious. To a certain extent, the labor force and machinery for the promotion of the main production area CLGP will have a contributing effect on the main marketing area of the market.

Table 4. Telecoupling effects of different grain production region types.

		LR_Direct		
	B_A	**P_A**	**M_A**	**P+M_A**
lnland	0.253 ***	0.173 **	0.284 ***	0.443 ***
	(−6.46)	(−2.5)	(−3.52)	(−7.67)
lnirra	0.157 ***	0.229 ***	0.176 ***	0.163 ***
	(−5.19)	(−7.29)	(−3.66)	(−5.82)
lnlabor	0.197 ***	0.303 ***	0.253 ***	0.113 ***
	(−4.03)	(−6.4)	(−5.2)	(−3.38)
lntpam	−0.098 ***	0.091 **	0.103 **	0.255 ***
	(−2.73)	(−2.37)	(−2.14)	(−8.16)
rd	−0.120 ***	−0.028	−0.100 *	−0.02
	(−2.97)	(−0.58)	(−1.88)	(−0.48)
pgs	0.351 ***	0.162 ***	1.491 ***	0.680 ***
	(−3.67)	(−3.53)	(−17.1)	(−14.28)
lnfer	0.003	0.002	−0.008	−0.008
	(−0.49)	(−0.17)	(−0.64)	(−0.86)
GCI	0	0	0	0
	(−0.73)	(−1.00)	(−1.27)	(−0.58)
		LR_Indirect		
	B_A	**P_A**	**M_A**	**P+M_A**
lnland	0.664 ***	0.296 **	−0.392 *	0.285 **
	(−5.55)	(−2.01)	(−1.70)	(−2.27)
lnirra	−0.303 **	0.105	0.249 **	0.002
	(−2.41)	(−0.95)	(−2.21)	(−0.02)
lnlabor	−0.848 ***	0.14	0.880 ***	0.566 ***
	(−4.17)	(−1.32)	(−5.71)	(−5.69)
lntpam	−0.15	−0.104	−0.024	−0.276 ***
	(−1.01)	(−1.07)	(−0.18)	(−4.08)
rd	−0.005	0.018	−0.209	0.178 *
	(−0.05)	(−0.2)	(−1.43)	(−1.72)
pgs	−0.807 ***	−0.051	0.073	−0.138 **
	(−2.63)	(−0.95)	(−0.28)	(−1.96)
lnfer	−0.022	−0.003	0.016	0.01
	(−1.59)	(−0.16)	(−0.48)	(−0.49)
GCI	0	0	0.000 **	0
	(−1.36)	(−0.35)	(−2.03)	(−0.91)
		LR_Total		
	B_A	**P_A**	**M_A**	**P+M_A**
lnland	0.917 ***	0.469 **	−0.107	0.728 ***
	(−6.99)	(−2.56)	(−0.41)	(−4.99)
lnirra	−0.146	0.334 ***	0.426 ***	0.165 *
	(−1.10)	(−2.77)	(−2.84)	(−1.75)
lnlabor	−0.651 ***	0.442 ***	1.133 ***	0.679 ***
	(−2.85)	(−3.54)	(−5.92)	(−6.3)
lntpam	−0.248	−0.012	0.079	−0.021
	(−1.45)	(−0.12)	(−0.52)	(−0.30)
rd	−0.125	−0.01	−0.309 *	0.158
	(−1.01)	(−0.09)	(−1.72)	(−1.42)
pgs	−0.456	0.112	1.564 ***	0.541 ***
	(−1.28)	(−1.6)	(−5.51)	(−7.08)
lnfer	−0.019	−0.001	0.008	0.002
	(−1.31)	(−0.05)	(−0.19)	(−0.07)
GCI	0	0	0.000 **	0
	(−1.39)	(−0.76)	(−2.17)	(−1.01)
Observations	341	403	217	620
R-squared	0.853	0.455	0.671	0.861
Number of ID	11	13	7	20

Note: (1) balanced production and marketing area—B_A; main grain-production area—P_A; main marketing area of grain—M_A; main production area and main marketing area—P+M_A; (2) ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

In the overall telecoupling effect of CLGP, it can be seen that the main factors affecting the CLGP area in producing the telecoupling effect are the area of cultivated land in each region and the agricultural labor force in each region. The factors affecting the main grain-producing areas in producing telecoupling effects are, in order of influence size, as follows: agricultural labor force > irrigated land > cultivated land in each region. Addressing those factors that affect the telecoupling effect factors of the main marketing area with the main production area, in the order of influence size, these are as follows: cultivated land area in each region > agricultural labor force > ratio of grain sown to total area sown with crops > irrigated area. In the telecoupling effect of the grain to the total area, factors such as the ratio of the area sown with grain to the total area with crops, agricultural labor force, irrigated area, disaster ratio, and GCI have significant telecoupling effects in the region; this is due to their own characteristics of low grain production and strong dependence on external demand for grain.

5. Discussion

5.1. Telecoupling between Regions

The telecoupling perspective is mainly utilized to observe whether a region far away from the subject of a study has an impact, and allows one to determine the size of its impact. Most of the scholars at home and abroad position this study as a study of spatial spillover effects. Zou and colleagues investigated how the transfer of rural labor affects the eco-efficiency of cultivated land use in different parts of China [32]. Their findings revealed a substantial spatial spillover effect, particularly in the western and northeastern regions, where the transfer of rural labor had a significant impact on promoting intensive and efficient land use practices. Tang [31] evaluated the spatial spillover effect of cultivated land utilization transition on grain production based on Hubei Province, showing that the spatial spillover effect of grain production in Hubei County is driven by the transfer generated by the amount of cultivated land, machinery inputs, and inputs of farmland irrigation infrastructure. Schneider quantified spatial spillovers from input inefficiencies in cultivated land production systems using DEA and a second-stage bootstrap truncated regression model [19]. All of the above studies confirmed the effect of spatial spillover of cultivated land production on neighboring regions or remote regions, but none of them cut into the perspective of telecoupling; also, they did not elaborate on the effect of telecoupling between regions on distant regions. Caron et al. emphasized the importance of multi-scale and multi-stakeholder governance in the food system. In the context of complex regional–national–global linkages, there can be dissonance and decoupling between the different groups, sectors, and regions involved in cultivated land grain production. It is crucial to develop a new framework that reconciles long-distance and close relationships, as well as addressing multi-scale ecologies and multi-group interests in order to effectively respond to these shifting dynamics [33]. After analyzing 609 questionnaires from 199 coastal villages in Oceania, Ferguson et al. [34] discovered that areas with high food import dependence tend to exhibit relatively low resilience to food system risk. Drawing fully on the science of sustainability and the meta-growth framework of global sustainability [35–37], this paper considers the telecoupling effects of CLGP across regions, discusses the drivers affecting cultivated land grain production, supply, and demand, coupled with human–land relations in telecoupling [25], and proposes policy implications accordingly.

5.2. Negative Factors Affecting CLGP

Based on the telecoupling effect of CLGP in China's interprovincial areas, arising from the interaction between the natural environment and the society and economy, the study explores the "flow" of its action and the factors affecting its telecoupling effect, and shows that the fertilizer application rate is a negative factor affecting the cultivated land yields and the degree of soil fertility. However, in previous studies, some scholars have proposed that the higher the fertilizer application rate in the region, the higher the grain production in the neighboring regions will be due to information sharing; thus, a positive effect of fertilizer application rate on CLGP is indicated [38]. It is worth noting that the amount of fertilizer application is proportional to the grain yield only within a certain range. When the application amount of organic fertilizer is guaranteed to ensure the fertility of cultivated land, the sustainable development of cultivated land for food can be promoted [39]. This also allows for further analysis and discussion of the spatial effects of organic fertilizers and conventional chemical fertilizers in promoting cultivated land grain production and generation.

5.3. Uncertainty Analysis

Telecoupling between regions is part of metacoupling [40], which involves a four-dimensional "coupled human and natural cube" (CHNC); this isa framework of telecoupling and proximity coupling, distant coupling and near-term coupling, explicit coupling and implicit coupling, and intra-group coupling and inter-group coupling [41,42]. By developing a conceptual analytical framework for interregional ecosystem service flows, SCHRÖTER utilizes four case studies to illustrate how the comprehension of interregional telecoupling systems can be enhanced within social–ecological systems [43]. This contributes to the enhancement of the capacity for sustainable management and policy options across regions. Research on food systems, with a focus on telecoupling and externalities, has proven to be an effective approach to addressing the challenges of localized governance. This perspective offers valuable insights into understanding and managing the complex interactions within food systems [44,45]. Based on CLGP, we must further analyze the impact of the international grain trade on cultivated land production on a spatial scale and dig deeper into the mutual changes between regions of cultivated land grain production and their laws on a temporal dimension. This is a way of strengthening our understanding of cultivated land grain production and promoting the exchange of domestic and international grain trade. At the same time, it is essential to fully consider the "people–land–industry" system that is involved in cultivated land grain production as a means of enhancing our understanding and facilitating exchanges in domestic and international trade in grain [46]. This will contribute to a comprehensive understanding of cultivated land grain production. It further explores the path of the high-quality development of cultivated land grain production, improves the interregional ecological environment, and promotes the friendly economic and social development of various regions.

6. Conclusions and Policy Implications

6.1. Conclusions

The present article analyzes the spatial and temporal characteristics of China's cultivated land grain output, identifies the direction and characteristics of the regional movement of China's regional grain output, and conducts a quantitative study of the "flow" of the promotion of telecoupling influence with the help of spatial analysis. Here, the main conclusions are summarized:

(1) China's CLGP has experienced a spiral rise over the past 30 years; the center of gravity of the production space has gradually shifted to the northeastern part of the country, the northern region has become an important region for China's grain production, and the southern region, especially the coastal area, has a high demand for grain. The telecoupling effect in this country is obvious.

(2) According to the measurement and analysis of the telecoupling effect of CLGP between provinces, it is concluded that the following factors are significantly and positively correlated with the total grain production: area of cultivated land in each region, irrigated area, agricultural labor force, agricultural machinery total power, and the ratio of grain to the total area sown with crops. These are positive factors in promoting spatial telecoupling between provinces. On the other hand, there is a negative correlation between the amount of fertilizer application amount and the damage ratio with the total grain production.

(3) From the decomposition of telecoupling benefits generated by China's CLGP, the following factors have a direct telecoupling effect on CLGP: the area of cultivated land in

each region, the irrigated area, the agricultural labor force, the total power of agricultural machinery, and the ratio of grain sown to total area sown with crops. Both the agricultural labor force and the ratio of grain sown to total area sown with crops have indirect remote spillover effects on CLGP between provinces. Meanwhile, the overall and zonal measurements of cultivated land grain production among provinces in China using the economic distance matrix also confirmed that CLGP showed significant telecoupling effects.

6.2. Policy Implications

(1) Telecoupling is connecting two or more subsystems at a distance, producing effective behavioral feedback relationships and influences. With the stable formation of China's CLGP pattern, the main grain-producing areas, the balance of production and marketing areas, and the main grain-marketing areas have formed a systematic interactive relationship, coupled with the natural environment and the economic and social long-distance linkage, jointly promoting the national grain security. The main grain-producing areas and the areas with balanced grain production and marketing need to further stabilize and improve the quality of cultivated land to meet the CLGP's objectives. Restoration and safeguarding of arable land, enhancing the quality standards for arable land, and implementing scientific approaches to crop management are key to increasing grain production and ensuring a steady supply of grain to the main grain-marketing areas. Innovative CLGP methods are needed for the main grain-marketing areas; on the basis of scientific management and the protection of existing cultivated land, publicity and policy support will be increased to encourage the existing agricultural labor force to engage in sustainable cultivation. These measures will promote sustainable coupled development between different systems.

(2) In response to the "flow" that promotes positive telecoupling effects between provinces and regions, in CLGP—in addition to establishing a reasonable cultivated land system—it is necessary to strengthen the construction of irrigation facilities and the management of agricultural water conservancy to ensure that cultivated land has excellent moisture. Modern agricultural mechanization techniques and equipment should be promoted. By promoting the construction of high-standard farmland, we can improve the efficiency and quality of cultivated land production and reduce the work intensity for agricultural laborers. Simultaneously, efforts are being made to enhance the training and skill level of the agricultural workforce, improving the quality of the workforce in the agricultural sector and increasing the productivity of cultivated land in grain production from every possible angle.

(3) In response to the "flows" between provinces that may lead to negative telecoupling, it is recommended that the utilization of organic fertilizers and bio-fertilizers is promoted. This is essential in minimizing the reliance on chemical fertilizers and pesticides. This will contribute to enhancing the organic matter in the soil, improving soil structure, and preventing the pollution of cultivated land. Furthermore, disaster prevention and mitigation need improvement. The effectiveness of farmland engineering in preventing, mitigating, and responding to disasters also needs improvement. The solid development of disaster prediction and early warning capabilities must be promoted. We must minimize the degree of disaster in the whole chain and in all directions. The enhancement of cultivated land grain production technology and risk prevention will enhance the positive telecoupling effect of CLGP between provinces; this will reduce the coupling threat that affects inter-provincial telecoupling exchanges or the conduct of grain trade.

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References

1. Agumas, B.; Balume, I.; Musyoki, M.K.; Benz, M.; Nziguheba, G.; Marohn, C.; Vanlauwe, B.; Cadisch, G.; Rasche, F. Agro-ecology, resource endowment and indigenous knowledge interactions modulate soil fertility in mixed farming systems in Central and Western Ethiopia. *Soil Use Manag.* **2021**, *37*, 367–376. [CrossRef]
2. Lu, M.; Gu, X.H.; Sun, Q.; Li, X.; Chen, T.E.; Pan, Y.C. Production Capacity Evaluation of Farmland Using Long Time Series of Remote Sensing Images. *Agriculture* **2022**, *12*, 1619. [CrossRef]
3. Deng, X.Z.; Huang, J.K.; Rozelle, S.; Uchida, E. Cultivated land conversion and potential agricultural productivity in China. *Land Use Pol.* **2006**, *23*, 372–384. [CrossRef]
4. Jiang, Y.L.; He, X.K.; Yin, X.G.; Chen, F. The pattern of abandoned cropland and its productivity potential in China: A four-years continuous study. *Sci. Total Environ.* **2023**, *870*, 161928. [CrossRef]
5. Shang, H.F.; Yi, X.Y.; Yin, C.B.; Chen, Y.J.; Zhang, Z.W. How Does the Stability of Land Management Right (SLMR) Affect Family Farms Cultivated Land Protection and Quality Improvement Behavior (CLPQIB) in China? *Land* **2021**, *10*, 1052. [CrossRef]
6. Cao, X.C.; Wu, N.; Adamowski, J.; Wu, M.Y. Assessing the contribution of China's grain production during 2005–2020 from the perspective of the crop-water-land nexus. *J. Hydrol.* **2023**, *626*, 130376. [CrossRef]
7. Chen, A.Q.; Hao, Z.; Wang, R.; Zhao, H.L.; Hao, J.M.; Xu, R.; Duan, H. Cultivated Land Sustainable Use Evaluation from the Perspective of the Water–Land–Energy–Food Nexus: A Case Study of the Major Grain-Producing Regions in Quzhou, China. *Agron. J.* **2023**, *13*, 2362. [CrossRef]
8. Wu, Y.F.; Yuan, C.C.; Liu, Z.X.; Wu, H.P.; Wei, X. Decoupling relationship between the non-grain production and intensification of cultivated land in China based on Tapio decoupling model. *J. Clean. Prod.* **2023**, *424*, 138800. [CrossRef]
9. Du, G.M.; Wang, X.Y.; Wang, J.Y.; Liu, Y.Y.; Zhang, H.N. Analysis of the Spatial-Temporal Pattern of the Newly Increased Cultivated Land and Its Vulnerability in Northeast China. *Land* **2023**, *12*, 796. [CrossRef]
10. Ma, L.B.; Dou, H.J.; Wu, S.S.; Shi, Z.H.; Li, Z.Y. Rural development pressure and "three-stay" response: A case of Jinchang City in the Hexi Corridor, China. *J. Rural Stud.* **2022**, *91*, 34–46. [CrossRef]
11. Zhao, S.X.; Xiao, D.Y.; Yin, M.M. Spatiotemporal Patterns and Driving Factors of Non-Grain Cultivated Land in China's Three Main Functional Grain Areas. *Sustainability* **2023**, *15*, 13720. [CrossRef]
12. Liu, J.G.; Hull, V.; Batistella, M.; Defries, R.; Zhu, C. Framing sustainability in a telecoupled world. *Ecol. Soc.* **2013**, *18*, 26. [CrossRef]
13. Yao, G.; Hertel, T.W.; Taheripour, F. Economic drivers of telecoupling and terrestrial carbon fluxes in the global soybean complex. *Glob. Environ. Chang. Hum. Policy Dimens.* **2018**, *50*, 190–200. [CrossRef]
14. Martín-López, B.; Felipe-Lucia, M.R.; Bennett, E.M.; Norström, A.; Peterson, G.; Plieninger, T.; Hicks, C.C.; Turkelboom, F.; García-Llorente, M.; Jacobs, S.; et al. A novel telecoupling framework to assess social relations across spatial scales for ecosystem services research. *J. Environ. Manag.* **2019**, *241*, 251–263. [CrossRef]
15. Sun, J. Understanding ecosystem services in a metacoupled world. *Trans. Earth Environ. Sustain.* **2023**, *1*, 46–54. [CrossRef]
16. Liu, J.; Yang, W.; Li, S. Framing ecosystem services in the telecoupled Anthropocene. *Front. Ecol. Environ.* **2016**, *14*, 27–36. [CrossRef]
17. Liu, H.M.; Fang, C.L.; Miao, Y.; Ma, H.T.; Zhang, Q.; Zhou, Q. Spatio-temporal evolution of population and urbanization in the countries along the Belt and Road 1950–2050. *J. Geogr. Sci.* **2018**, *28*, 919–936. [CrossRef]
18. Nef, D.P.; Kotra, K.K.; Stauffacher, M.; Six, J.; Kruetli, P. Vulnerability to Food Insecurity in a Telecoupled World: Insights from Vanuatu. *Front. Sustain. Food Syst.* **2022**, *6*, 818586. [CrossRef]
19. Schneider, K.; Skevas, I.; Oude, L. Spatial Spillovers on Input-specific Inefficiency of Dutch Arable Farms. *J. Agric. Econ.* **2020**, *72*, 224–243. [CrossRef]
20. Wu, Y.Z.; Shan, L.P.; Guo, Z.; Peng, Y. Cultivated land protection policies in China facing 2030: Dynamic balance system versus basic farmland zoning. *Habitat Int.* **2017**, *69*, 126–138. [CrossRef]
21. Liu, J.G.; Mooney, H.; Hull, V.; Davis, S.J.; Gaskell, J.; Hertel, T.; Lubchenco, J.; Seto, K.C.; Gleick, P.; Kremen, C.; et al. Systems integration for global sustainability. *Science* **2015**, *347*, 1258832. [CrossRef] [PubMed]
22. Zimmerer, K.S.; Lambin, E.F.; Vanek, S.J. Smallholder telecoupling and potential sustainability. *Ecol. Soc.* **2018**, *23*, 1–30. [CrossRef]
23. Liu, J.G.; Dietz, T.; Carpenter, S.R.; Taylor, W.W.; Alberti, M.; Deadman, P.; Redman, C.; Pell, A.; Folke, C.; Ouyang, Z.; et al. Coupled human and natural systems: The evolution and applications of an integrated framework. *Ambio* **2021**, *50*, 1778–1783. [CrossRef] [PubMed]

24. Bicudo, S.R.F.; Batistella, M.; Palmieri, R.; Dou, Y.; Millington, J.D. Eco-certification protocols as mechanisms to foster sustainable environmental practices in telecoupled systems. *Forest Policy Econ.* **2019**, *105*, 52–63. [CrossRef]
25. Sonderegger, G.; Oberlack, C.; Llopis, J.C.; Verburg, P.H.; Heinimann, A. Telecoupling visualizations through a network lens: A systematic review. *Ecol. Soc.* **2020**, *25*, 47. [CrossRef]
26. Dou, Y.; Millington, J.D.A.; Bicudo, R.F.; Silva, D.; Mccord, P.; Viña, A.; Song, Q.; Yu, Q.; Wu, W.; Batistella, M.; et al. Land-use changes across distant places: Design of a telecoupled agent-based model. *J. Land Use Sci.* **2019**, *14*, 191–209. [CrossRef]
27. Carlson, A.; Zaehringer, J.; Garrett, R.; Ramon, F.B.S.; Furumo, P.; Raya Rey, A.; Torres, A.; Gon, C.M.; Li, Y.; Liu, J. Toward rigorous telecoupling causal attribution: A systematic review and typology. *Sustainability* **2018**, *10*, 4426. [CrossRef]
28. Tobler, W.R. A Computer Movie Simulating Urban Growth in the Detroit Region. *Econ. Geogr.* **2016**, *46*, 234–240. [CrossRef]
29. Fingleton, B.; Le Gallo, J.; Pirotte, A. Panel data models with spatially dependent nested random effects. *J. Reg. Sci.* **2018**, *58*, 63–80. [CrossRef]
30. Lesage, J.; Pace, R.K. *Introduction to Spatial Econometrics*; Chapman & Hall/CRC Press: Boca Raton, FL, USA, 2009; pp. 19–44.
31. Tang, Y.; Lu, X.; Yi, J.; Wang, H.; Zheng, W. Evaluating the spatial spillover effect of farmland use transition on grain production–an empirical study in hubei province, China. *Ecol. Indic.* **2021**, *125*, 107478. [CrossRef]
32. Zou, X.Q.; Xie, M.H.; Li, Z.Y.; Duan, K.F. Spatial Spillover Effect of Rural Labor Transfer on the Eco-Efficiency of Cultivated Land Use: Evidence from China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9660. [CrossRef] [PubMed]
33. Caron, P.; Ferrero y de Loma-Osorio, G.; Nabarro, D.; Hainzelin, E.; Guillou, M.; Andersen, I.; Arnold, T.; Astralaga, M.; Beukeboom, M.; Bickersteth, S.; et al. Food systems for sustainable development: Proposals for a profound four-part transformation. *Agron. Sustain. Dev.* **2018**, *38*, 41. [CrossRef] [PubMed]
34. Ferguson, C.E.; Tuxson, T.; Mangubhai, S.; Jupiter, S.; Govan, H.; Bonito, V.; Alefaio, S.; Anjiga, M.; Booth, J.; Boslogo, T.; et al. Local practices and production confer resilience to rural Pacific food systems during the COVID-19 pandemic. *Mar. Pol.* **2022**, *137*, 104954. [CrossRef] [PubMed]
35. Liu, J.G. Leveraging the metacoupling framework for sustainability science and global sustainable development. *Natl. Sci. Rev.* **2023**, *10*, nwad090. [CrossRef] [PubMed]
36. Manning, N.; Li, Y.J.; Liu, J.G. Broader applicability of the metacoupling framework than Tobler's first law of geography for global sustainability: A systematic review. *Geogr. Sustain.* **2023**, *4*, 6–18. [CrossRef]
37. Mertz, O.; Corbera, E.; Busck-Lumholt, L.M.; Coenen, J.; Persson, J.; Pedersen, A.F. Telecoupling as a framework to support a more nuanced understanding of causality in land system science. *J. Land Use Sci.* **2022**, *17*, 386–406. [CrossRef]
38. Yang, Z.H.; Cai, H.Y.; Qin, C.; Liu, H.G. Analysis on the Spatial and Temporal Pattern of China's Grain Production and Its Influencing Factors. *J. Agric. Sci. Technol.* **2018**, *20*, 1–11. (In Chinese) [CrossRef]
39. Jin, X.; Cai, J.W.; Yang, S.Y.; Li, S.P.; Shao, X.J.; Fu, C.M.; Li, C.Z.; Deng, Y.; Huang, J.Q.; Ruan, Y.Z.; et al. Partial substitution of chemical fertilizer with organic fertilizer and slow-release fertilizer benefits soil microbial diversity and pineapple fruit yield in the tropics. *Appl. Soil Ecol.* **2023**, *189*, 104974. [CrossRef]
40. Liu, M.B.; Xiong, Y.F.; Zhang, A.L. Multi-scale telecoupling effects of land use change on ecosystem services in urban agglomerations—A case study in the middle reaches of Yangtze River urban agglomerations. *J. Clean. Prod.* **2023**, *415*, 137878. [CrossRef]
41. Liu, H.; Fang, C.L.; Fang, K. Coupled human and natural cube: A novel framework for analyzing the multiple interactions between humans and nature. *J. Geogr. Sci.* **2020**, *30*, 355–377. [CrossRef]
42. Cui, X.; Fang, C.L.; Liu, H.; Liu, X.; Li, Y. Dynamic simulation of urbanization and eco-environment coupling: Current knowledge and future prospects. *J. Geogr. Sci.* **2020**, *30*, 333–352. [CrossRef]
43. Schierhorn, F.; Meyfroidt, P.; Kastner, T.; Kuemmerle, T.; Prishchepov, A.V.; Müller, D. The dynamics of beef trade between Brazil and Russia and their environmental implications. *Glob. Food Secur.* **2016**, *11*, 84–92. [CrossRef]
44. Eakin, H.; Rueda, X.; Mahanti, A. Transforming governance in telecoupled food systems. *Ecol. Soc.* **2017**, *22*, 32. [CrossRef]
45. Millington, J.D.A.; Xiong, H.; Peterson, S.; Woods, J. Integrating Modelling Approaches for Understanding Telecoupling: Global Food Trade and Local Land Use. *Land* **2017**, *6*, 56. [CrossRef]
46. Tian, Y.; Shi, X. Analysis of Dynamic Evolution and Driving Factors of Low-Carbon Utilization Efficiency of Cultivated Land in China. *Agriculture* **2024**, *14*, 526. [CrossRef]